The TREND IN ENGINEERING

at the University of Washington

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MODEL STUDY OF SEWAGE POLLUTION IN PUGET SOUND

PLASTER CRACKING AS A MEASURE OF BUILDING MOTION

AN ANALOG COMPUTER METHOD FOR SOLVING SETS OF NON-LINEAR ALGEBRAIC EQUATIONS

MAGNESIUM FROM OLIVINE *via* CHLORINATION: A POSSIBILITY

LAMINAR HEAT TRANSFER FROM A UNIFORMLY HEATED FLAT PLATE AT MACH 2.5

January, 1956

Published quarterly by

THE ENGINEERING EXPERIMENT STATION

*When Is an Engineer a Professional?**

THE DEMAND FOR ENGINEERS is increasing faster than the supply. It is estimated, for example, that the annual rate of requirement for new engineering graduates in the U. S. is about 35,000. In 1955 only 23,000 will graduate; in '56 an estimated 30,000 and in '57 only 34,000.

Since the man in the street is also becoming more engineering conscious we should have every reason to expect that the engineer would be very well satisfied, that the individuals in the profession would be challenged by the demand for their services, moving confidently up to their opportunities and happy and secure in the realization of the increasing importance of their work to all of us.

However, we in industry have been taken aback to find engineers confused, dissatisfied and at odds one with another, or in the words of a study conducted by the University of Chicago "Engineers in industry seem to be far more frustrated than satisfied."

If engineers want the privileges, status and pay of professionals, they must act like professionals and accept professional responsibilities. On the other hand, if they shun those responsibilities then no matter how fondly they may hope, nor how loudly they may protest, they will be inevitably and completely non-professional. The choice is just as simple as that. It is also as inescapable as that. . . .

Industry expects that if the engineer claims engineering as a profession, he has the responsibility to work like a professional. That requires no less than a complete mental honesty, a self-discipline and a devotion in every engineering endeavor that he undertakes. As independently as possible of his own feelings, the environmental factors, other personalities involved and even his own chances for loss or gain, his responsibility in the face of an engineering assignment that he has accepted is singular, namely to complete it to the very best of his ability, training, experience and skill. This is the distinguishing mark of the professional. The professional is in a sense impersonal, almost selfless in the practice of his profession. This is the quality that enables the attorney to conduct his most brilliant defense for a client whose case seems hopeless, or for the doctor to heal his enemy. . . .

The second thing industry expects is that if the engineer claims engineering as a profession, he has the responsibility to live like a professional. This concept was ably stated by that brilliant scholar, Robert MacIver, formerly Lieber Professor of Political Philosophy and Sociology at Columbia University: "Each profession tends to leave its distinctive stamp upon a man; so that it is easier in general to distinguish say the doctor, the priest, the teacher or the judge . . . than it is to discern, outside their work, the electrician from the railway man or the plumber from the machinist."

The engineer's responsibility to industry is just as high in this regard as the doctor's to his patient or the lawyer's to his client. . . .

Because . . . the great majority of engineers are employed, they apparently have made the mistake of assuming that they could behave just like non-professional employees do both in their personal and in their social relationships. Careful observers of the trends and developments of engineering have long been warning against such a fallacy. For example, W. J. King . . . had this to say:

"Some years ago the author became very much impressed with the fact which can be observed in any engineering organization that the chief obstacles to the success of individual engineers or of the group comprising a unit were of a personal . . . rather than a technical nature. It was apparent that both the author and his associates were getting into much more trouble by violating the unwritten laws of professional conduct than by committing technical sins against the well-documented laws of science. . . . But in many respects these (unwritten) laws are like the basic laws of society; they cannot be violated too often with impunity, notwithstanding striking exceptions in individual cases."†

Later the Carnegie Foundation study, under the direction of C. R. Mann, concluded that personal and social competence contribute to about 67 per cent of an individual engineer's ability to succeed in his profession, that is, one-third technical, two-thirds personal and social. . . .

In hoping or attempting to be a true professional the engineer has a responsibility to keep himself up to date. The requirement to continue self-education is in itself an additional distinguishing mark of the professional man.

In industry we expect the engineer to keep himself up to date in the developments of his particular

(Continued on page 34)

* Excerpts from "The Engineer's Responsibility to Industry," a paper presented by Gerry E. Morse, Vice President, Industrial Relations, Minneapolis-Honeywell Regulator Co., before the Conference on Professional Development sponsored by the NSPE at Philadelphia.

† "The Unwritten Laws of Engineering," *Mech. Engin.*, May, June, July, 1944.

THE ENGINEERING EXPERIMENT STATION of the University of Washington was established in December, 1917, to coordinate investigations in progress and to facilitate the development of engineering and industrial research in the University. Its purpose is to aid in the industrial development of the state and nation by scientific research and by furnishing information for the solution of engineering problems.

The scope of the work is three-fold:

1) to investigate and publish information concerning engineering problems of a more or less general nature that would be helpful in municipal, rural, and industrial affairs;
2) to undertake extended research and to publish reports on engineering and scientific problems;
3) to provide opportunities for graduate engineers to conduct research under conditions that will most effectively prepare them for professional service.

For administrative purposes the work of the Station is organized into eight divisions:

1. Aeronautical Engineering
2. Chemical Engineering, Industrial Chemistry
3. Civil Engineering
4. Electrical Engineering
5. Forest Products
6. Geology
7. Mechanical Engineering
8. Mining, Metallurgical, Ceramic Engineering

The control of the Station is vested in a Station Board consisting of the President of the University, the Dean of the College of Engineering as chairman, the Director of the Station, and members of the faculty, representative of the administrative divisions. The Board determines the character of the investigations to be undertaken and supervises the work.

The Station offers a substantial number of research fellowships to highly qualified graduate students who work under the direct supervision of the faculty of the various divisions. Results of major investigations are published in the form of bulletins and reports. Current research findings from the Station's fellowship projects, as well as accounts of its activities, appear in the quarterly journal, *The Trend in Engineering at the University of Washington*. Reprints of articles by members of the engineering faculty and graduate students published in recognized technical journals are also issued by the Station. Requests for copies of the publications and inquiries for information on engineering and industrial problems should be addressed to the Director, Engineering Experiment Station, University of Washington, Seattle 5.

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IN ENGINEERING

at the University of Washington

Vol. 8 No. 1

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FIG. 1. HYDRAULIC MODEL OF PUGET SOUND

Professor Tyler (*right*) and Dr. Maurice Rattray of the Oceanography Department are inspecting the dye applicator. (1) Olympia, (2) Tacoma, (3) Seattle, (4) Everett, (5) fresh water supply to rivers, (6) Strait of Juan de Fuca. Each "square" of the 5'-longitude—5'-latitude grid represents approximately 21.7 square miles.

A MODEL STUDY OF SEWAGE POLLUTION IN PUGET SOUND

RICHARD G. TYLER
Professor of Sanitary Engineering

ERNEST H. ROGERS and WILLIAM S. TSAO *
Graduate Students in Sanitary Engineering

R. G. Tyler

The use of hydraulic models for determining the flow patterns and associated problems for rivers and tidal estuaries, both here and abroad, has aided greatly in clarifying many problems too complex for satisfactory analytical clarification without their aid. The present investigation has further emphasized their usefulness in obtaining an understanding of the detailed water movements in that very complicated tidal estuary in the State of Washington: Puget Sound. The authors believe that the information obtained from the relatively small model here used, provides a more comprehensive and accurate concept of the pollution build-up in the Sound and the latter's capacity to handle it, than could have been obtained in any other available manner. Although small models have the disadvantage of being less accurate than larger ones, so long as their accuracy is adequate for the particular research under consideration, they have great advantages in savings in the costs of construction and operation and especially in required research time. Test conditions can be changed more rapidly and easily than in larger units, and relatively stable conditions for new test requirements can be more quickly established.

Puget Sound extends about 80 miles in a southerly direction from the eastern end of the Strait of Juan de Fuca and covers an area of roughly 95 miles north and south and 40 miles east and west. (See map, page 6.) It drains an area of some 11,000 square miles where annual precipitations vary locally from about 30 to a maximum estimated at 200 in. per year,[1] depending on altitude and orientation. The combined mean annual flow of its principal rivers is about 40,000 cfs while an addition 10,000 cfs reaches the Sound overland or through small creeks.

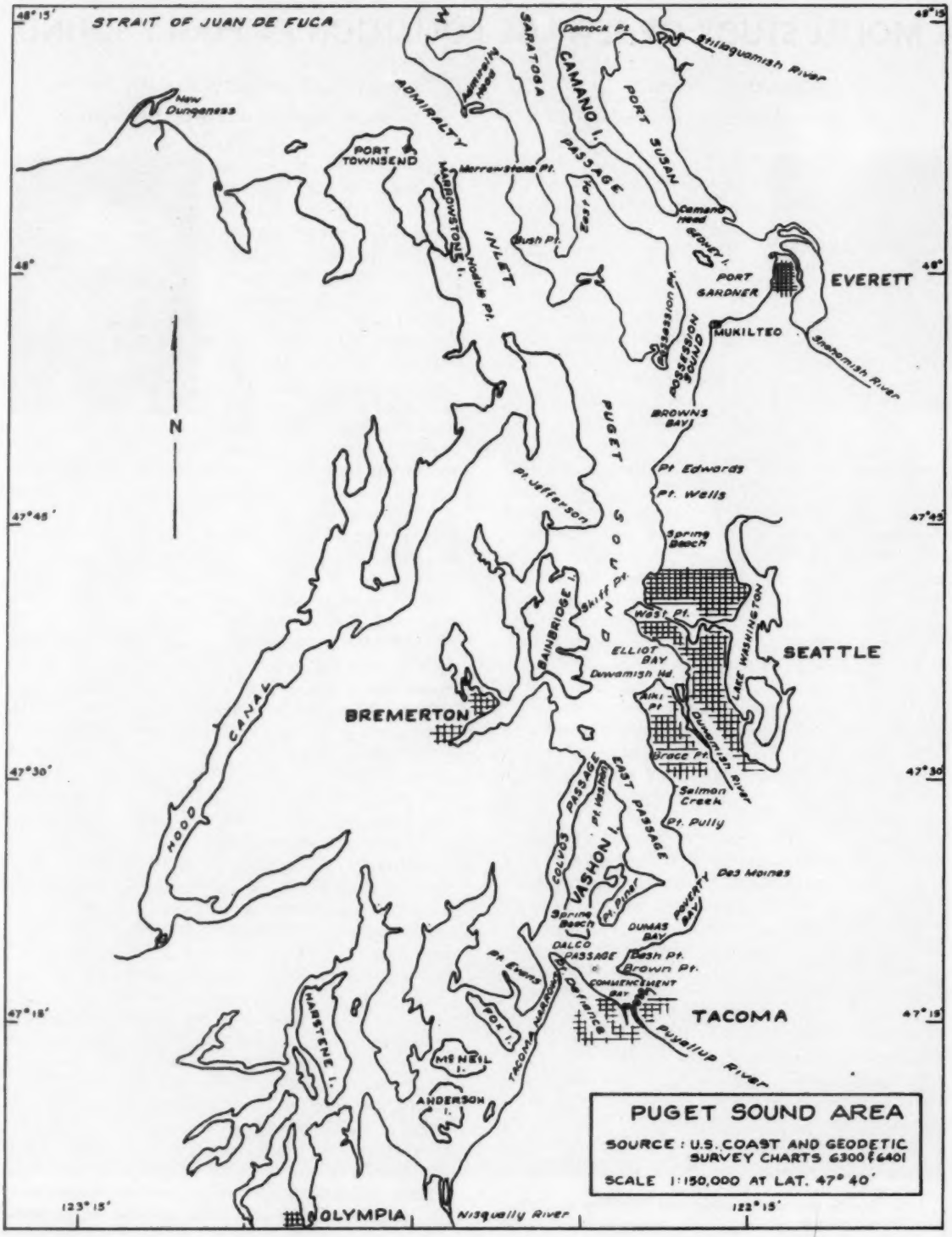
Its water surface totals some 1,015 square miles, while its depth varies from about 240 ft over the entrance sill from the Strait to 600 to 800 ft opposite Seattle. Local depths approach 1,000 ft. The average tidal range is 9.28 ft with a time differential from the Strait of 38 min at Seattle and 1 hr 23 min at Olympia.

E. H. Rogers

Several years ago a tidal model of Puget Sound sponsored by the Office of Naval Research was constructed by the University of Washington's Department of Oceanography as an aid in both its teaching and research programs. The Department has also developed ingenious and easily used devices for producing and measuring with great accuracy in the model the complicated water movements and velocities, salinities, stratification, and general behavior that occur in nature. For a detailed description of the model, its instrumentation and calibration, one should see Technical Report No. 19, Department of Oceanography, University of Washington.[2] The model (Fig. 1) is built to a scale of 1:40,000 horizontal and 1: 1,152 vertical, with a Reynolds number of 500. The time scale is 1: 1,178 so that a day is 1.2 minutes in the model, and a year is 7.44 hours. This makes it possible to follow, in a relatively short time interval, movements of sewage from any existing or proposed outfall till it reaches the Strait. The total volume of the model below the mean lower low water level is 24.2 gal, which represents 26.5 cubic miles in nature. The tidal exchange averages 1.15 gal representing 1.26 cubic miles in the prototype.

The model is only about 7 by 15 ft, with a maximum depth of 10 in. and of 2 in. over the critical sills, as at the entrance from the Strait. Because of the small scale of the model, it has been particularly important to check its operation and behavior against the prototype. After extensive investigations and some slight local modifications of the model, the Oceanography Department has been able to reproduce very closely the tidal and current behavior of the Sound and the amplitude, time, distribution of sea and fresh waters, and typical flow patterns, all of which can be both observed as they occur and recorded by sensitive mechanisms for later study. Our conclusion after a year's study and operation of the model is that the dyes used to simulate sewage and industrial wastes, when discharged in appropriate quantities at the various existing and other possible or probable

* Mr. Tsao is now with Gardner and Hitchings, consulting engineers, in Seattle.


STRAIT OF JUAN DE FUCA
New Dungeness
PORT TOWNSEND
ADMIRALTY INLET
SARATOGA PASSAGE
CAMANO I.
PORT SUSAN
Camano Head
Davock Pt.
Stillaguamish River
Marrowstone Pt.
Bush Pt.
Hadlock
Indian Pt.
Point Wilson
Marrowstone I.
Admiralty Inlet
Possession Sound
PORT GARDNER
EVERETT
MUKILTEO
Snohomish River
BROWNS BAY
Pt. Edwards
Pt. Wells
Spring Beach
Pt. Jefferson
PUGET SOUND
BAINBRIDGE I.
Skiff Pt.
West Pt.
ELLIOT BAY
Duwamish Hd.
SEATTLE
LAKE WASHINGTON
Alki Pt.
Duwamish River
BREMERTON
HOOD CANAL
Brace Pt.
Salmon Creek
Pt. Pully
EAST PASSAGE
COLVOS PASSAGE
Pt. Heyer
VASHON I.
Des Moines
Pt. Dalby
POVERTY BAY
Spring Beach
DUNAS BAY
DALCO PASSAGE
Dash Pt.
Brown Pt.
COMMENCEMENT BAY
Pt. Evans
TACOMA
Tacoma Harbor
Entrance
Puyallup River
HARSTENE I.
Fox I.
McNEIL I.
ANDERSON I.
OLYMPIA
Nisqually River
N
48° 15'
48°
47° 45'
47° 30'
47° 15'
123° 15'
122° 15'
PUGET SOUND AREA
SOURCE : U.S. COAST AND GEODETIC SURVEY CHARTS 6300 & 6401
SCALE 1:150,000 AT LAT. 47° 40'

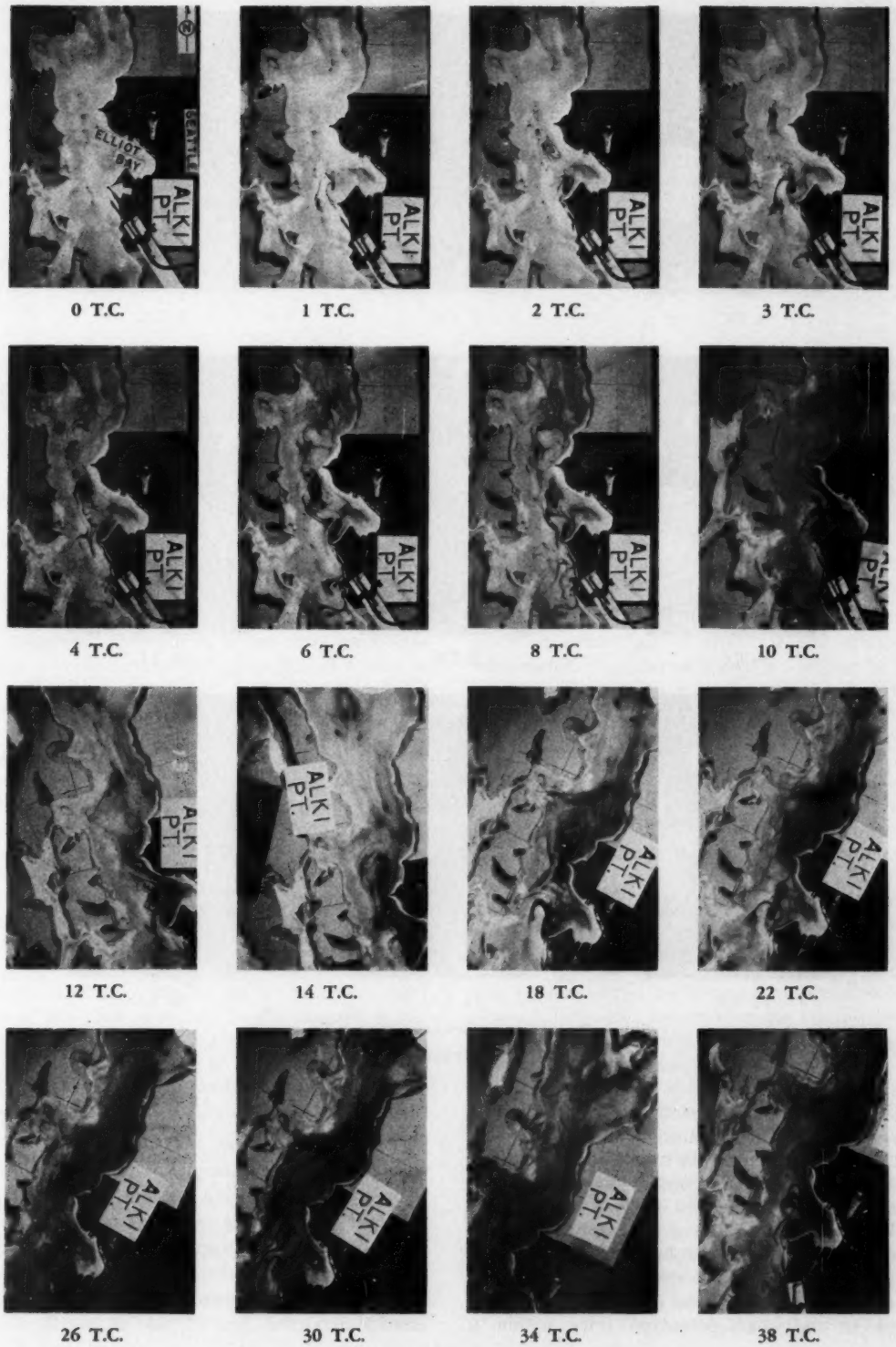


FIG. 2. ALKI POINT: SURFACE WATER TRANSPORT
T.C: Tidal Cycle

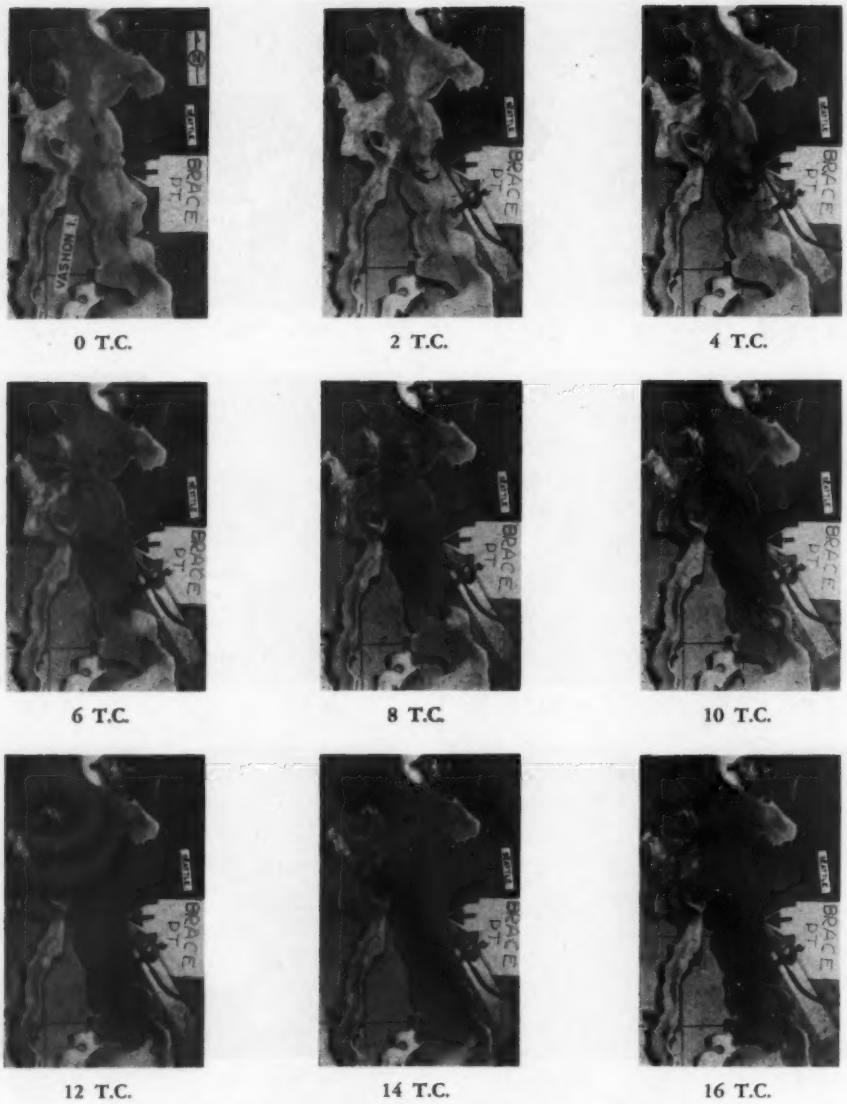


FIG. 3. BRACE POINT: SURFACE WATER TRANSPORT

T.C: Tidal Cycle

outfall sites, present a sufficiently accurate reproduction of sewage movements throughout the part of the Sound discussed herein, to be of considerable assistance in clarifying and recording the complicated movements of the sewage as it passes through the sound and out into the Strait of Juan de Fuca.

Studies by the Oceanography Department before constructing the model, indicated that a minimum of six of the more important tidal constituents would be required to reproduce prototype tides within a deviation of $\pm$ 1 ft. Cams and gear ratios for producing these constituent movements were employed, using many of the principles of the Coast and Geodetic Survey's tide-predicting machine. By using only two of these cams, simple repeating average tides can be reproduced. These average tides were used in the investigation herein discussed for purposes of simplifying the tidal movements and thus obtaining greater clarity.

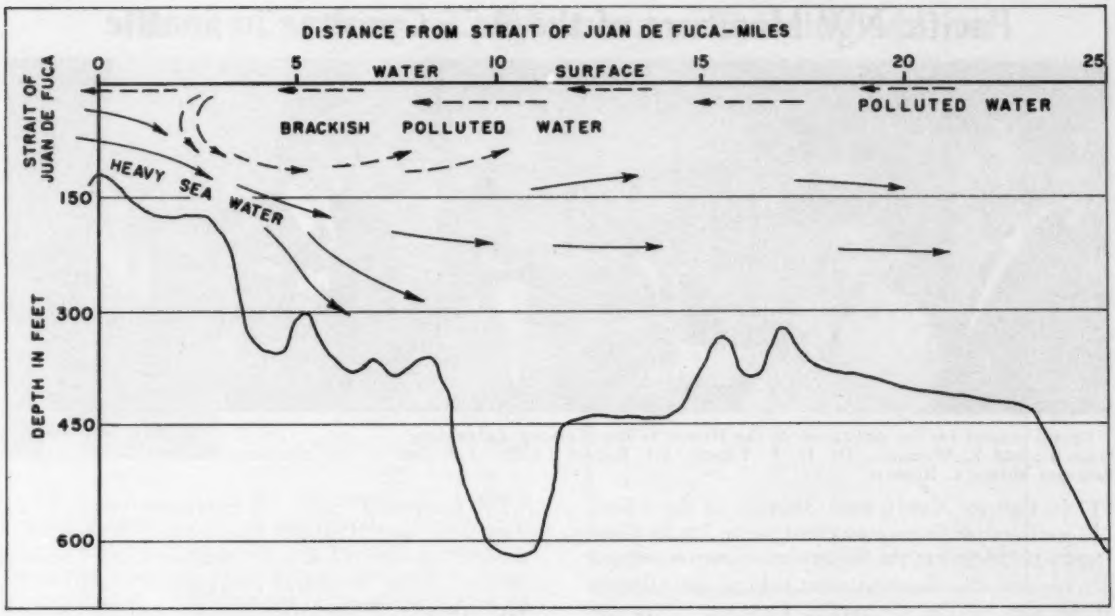


FIG. 4. VERTICAL LONGITUDINAL SECTION OF ADMIRALTY INLET SHOWING VERTICAL CURRENTS PRODUCED BY FRESH AND SEA WATER STRATIFICATION

The integrated movements of the cams are translated into a vertical reciprocating motion of a float in the model head box shaped to duplicate, by its varying displacement, the tidal inflow and outflow at the entrance to Admiralty Inlet from the Strait. Tidal movements have been checked throughout the model both as to height and timing, which show that it can reproduce any calendar tidal sequence or repeat an average, maximum or minimum tide as desired.

Provision is also made to introduce the fresh water river flow from the eleven major rivers having a mean annual flow of from 400 to 16,000 cfs. Each river consists of a vertical, upward-flow glass tube, partly filled with sand, calibrated to deliver the desired range of flows occurring in nature with the quantity of flow indicated by the height of expanded sand column in the tube produced by the upward water velocity and read on an appropriate scale. The additional salt solution required to maintain the desired salinity in the model is automatically supplied. The effects of maximum and minimum river flows can therefore be investigated wherever desired. No provision has been made to duplicate wind effects.

The Department of Civil Engineering has made, for instructional purposes, a colored moving picture of tidal movements in the model at various existing and other potential sewer outfall locations. But space limitations will only permit the showing in this article, of photographs illustrating the type of information the model can furnish with reference to possible sewer outfall sites for the sewage flow anticipated from the southwestern section of Seattle. These will serve to indicate something of the extremely complex and unusual tidal movements which occur in Puget Sound and to illustrate the use of the model in studying these movements.

To illustrate one of the unusual tidal movements which we observed first in the model and then checked by available tidal data, pictures are shown in Figs. 2 and 3 which indicate the direction and extent of tidal movements by observing the movements of dye simulating the discharge from a sewer, as photographed at successive occurrences of high slack, at two potential outfall locations for the discharge of West Seattle sewage into the Sound. These two sets of pictures can be considered as being taken simultaneously at the two locations. By showing the sewage "front" at each high slack period, the direction and extent of movement of the sewage in the Sound can be readily seen. It is obvious that sewage discharged at Alki Point (Fig. 2) proceeds to travel principally outward toward the Strait as its net movement, while shuttling back and forth with the incoming and outgoing tides but with some loss of sewage to the south. It is equally apparent that while some of the sewage from the Brace Point hypothetical outfall site (Fig. 3) moves northward with that from Alki Point, most of it works its way south to the Tacoma Narrows into which it is drawn and thoroughly mixed by the

(Continued on page 34)

Pacific NW Members of the ACS Convene in Seattle

Group present for the dedication of the Hewitt Wilson Ceramic Laboratory. (*L. to r.*) **Dr. J. I. Mueller, Mrs. Wilson, Dean Harold E. Wessman, Dr. H. F. Yancey, Mr. Robert Twells (President of the American Ceramic Society), Dean Emeritus Milnor C. Roberts.**

THE PACIFIC NORTHWEST SECTION of the American Ceramic Society was host to the Pacific Coast Regional Meeting of the Society in Seattle on October 27, 28, and 29. Sessions were held at the Olympic Hotel and on the University Campus. Over 300 people participated in the activities of the meeting.

An Industry-Education Conference devoted to a discussion of Student Engineer Training Programs began the formal part of the meeting, following greetings from Hal J. Kelly, Chairman of the PNW Section. Mr. Kelly is in charge of non-metallic materials testing for the U. S. Bureau of Mines on the University Campus. In the discussion of summer employment for engineering students, Clarence E. Nordquist, junior in Ceramic Engineering at the University, presented the student's viewpoint; Neal R. Fosseen, University alumnus and now President of the Washington Brick and Lime Co., Spokane, represented industry; and Dr. J. I. Mueller, Professor of Ceramic Engineering, discussed summer employment as an education medium.

A general session Thursday afternoon was devoted to discussions of production problems and quality control. Participants in this session were from the Los Angeles area, with the exception of Prof. Berl W. Owens, of the Mechanical Engineering Department of the University.

Friday was devoted to technical sessions including Basic Science, Glass, Structural Clay Products, Refractories, Materials and Equipment, Whitewares, and Enamels. In the afternoon a Glass-Refractories Joint Session was held, and the Structural Clay Products Session featured a symposium on Prestressed Ceramic Components. Much of this discussion was based on work done in the Engineering Experiment Station.

Dr. J. I. Mueller appeared on these programs, as author or co-author, as follows:

"A Continued Study of Extrusion (with F. H. Simpson), and "Use of Lignosite in Stiff-Mud Extrusion" (with E. G. King), Structural Clay Products Session; "Slag Testing of Refractories" (with S. W. McCormick), Refractories Session; and "A Study of Enamels for Aluminum" (with J. E. Shoffner), Enamels Session.

Prof. R. J. Campbell, Jr., spoke on "A Furnace for High-Temperature X-Ray Crystallographic Analysis" before the Basic Science Session, and Howard A. McDonald, former graduate student and EES research assistant, now with the Kaiser Aluminum and Chemical Corporation at Spokane, presented "Problems Encountered in Using Plastic Refractories for Aluminum Melting" at the the Refractories Session.

Activities Saturday moved to the University of Washington campus for the dedication of the Hewitt Wilson Ceramic Laboratory. Mrs. Wilson was present from Fullerton, California, as well as many of Dr. Wilson's former students. Dr. Wilson founded the Ceramic Engineering Division at the University in 1920, and was responsible for a great deal of ceramic work in the Pacific Northwest. Speakers at the dedication were A. Lee Bennett, Vice President of Pacific Clay Products Co., Los Angeles, representing Ceramic Engineering alumni from the University; Oliver C. Ralston, Chief Metallurgist of the U. S. Bureau of Mines, Washington, D. C.; Milnor C. Roberts, former Dean of the College of Mines at the University; and Harold E. Wessman, Dean of the College of Engineering at the University. A terra cotta plaque with details of Dr. Wilson's background has been installed on the exterior of the laboratory.

Prior to the meeting Robert Twells, President of the American Ceramic Society, visited the Ceramic Engineering Division. Following conferences with the staff and a tour of the facilities, Mr. Twells met with the ceramic engineering students.

Plaster Cracking as a Measure of Building Motion

ALFRED L. MILLER

Professor of Mechanics and Structures

A. L. Miller

Cracks in plastered walls and ceilings are unmistakable evidence of structural deformation and motion. To the general public, they are both vexatious and perplexing, but to the experienced observer they signify the kind and amount of deformation and the probable cause. Cracks caused by earthquake motion are difficult to interpret because in the sequence of motions cracks are formed, opened, and closed, and yield little information concerning the deformations involved in the event, especially in buildings that are not otherwise damaged. The purpose of this study was to determine the magnitude of deformation required to cause cracking and to examine the feasibility of calibrating the observations.

Studies of crack patterns caused by an earthquake give a reasonably clear picture of the type of deformation and the direction of motion but leave the amount of displacement as a matter of conjecture. Diagonal tension cracks in plastered walls and ceilings are typical earthquake effects that result from the skewing or shear deformation of the diaphragms. Gypsum plaster is the most widely used surfacing material, and its physical properties are well known except the magnitude of strain at which diagonal tension cracks will appear. For this reason, tests to explore the possibility of using the cracking of gypsum plaster as a criterion of lateral motion were made in conjunction with the thesis "The Evaluation of Lateral Building Motion Due to Earthquakes" by H. N. Dulagil (M.S. in Civil Enginering, December, 1954). The results show that such a criterion is valid and indicate its magnitude.

Skewing is defined as the deformation of an initially rectangular surface to a rhomboidal shape. Principal strains in diagonal compression and diagonal tension are induced, causing diagonal tension cracks in brittle materials. Many materials, including gypsum plaster, can endure a limited amount of such deformation without cracking. When that limit is reached, cracks form and demonstrate that the limit has been exceeded. This limit is called the "cracking modulus." It is evaluated as the angle through which a reference line which is normal to the imposed motion is rotated when cracking occurs, and is expressed in terms of slope ratio. The strength of the material is irrelevant to the subject and is intentionally omitted from this report in order that attention will not be diverted from the significance of the findings.

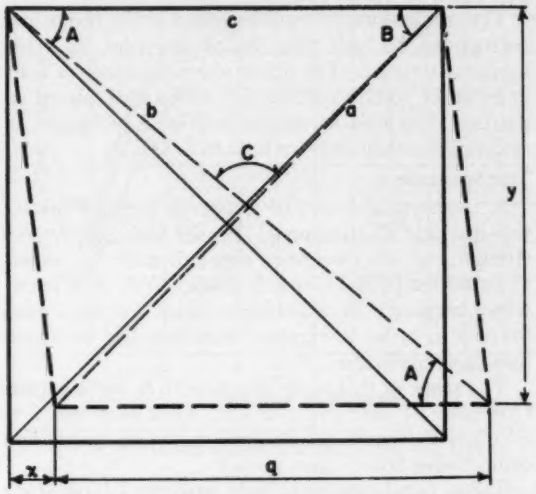


FIG. 1. DIAGRAM SHOWING EXACT METHOD OF CALCULATION

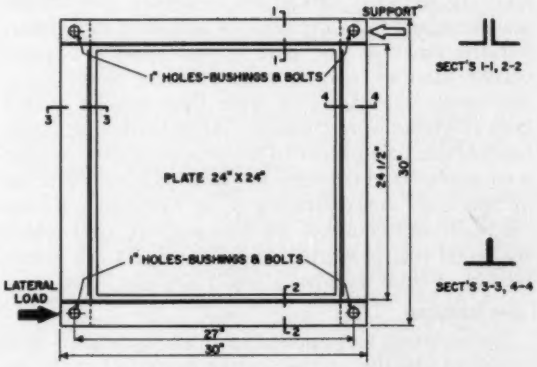


FIG. 2. DIAGRAM OF TESTING FRAME

Test Procedure

Skewing deformation was imposed on a flat plate on which gages were mounted in a square pattern for the measurement of the change in lengths of the diagonals, as shown diagramatically by Fig. 1. From the observed data the displacement, x, is calculated, and the cracking modulus is expressed by x/y.

The structural steel test frame for 24-in. square specimens was assembled by four corner bolts, two of which secured one edge to the supporting table. Deformations were applied by means of a calibrated hydraulic jack acting along the opposite edge (Fig. 2). Friction was largely eliminated.

The test specimens were mounted in the frame and surrounded by soft fibre board in order to avoid localized stresses. The gages were mounted on bolts in an 18-in. square pattern, and wires were placed on the two diagonals as shown in Fig. 3. Changes in diagonal dimensions were read to 0.0001 in.

Test Specimens

A commercial brand of unfibered gypsum plaster was used for all specimens. Tensile and compressive strengths of all specimens approximated the values as published by the Gypsum Association. Specimens were prepared in accordance with recommended practice in order to simulate materials and construction in common use.

The scope of this study was limited to eight panels. One plate of neat gypsum 1 in. thick was tested to correlate the panel results with the basic tensile and compressive tests.

Three panels of wood lath base on 2-by-4 studs and four panels of expanded metal lath on 2-by-4 studs were prepared. Before the plaster was applied all were skewed sufficiently to reduce mechanical resistance and to assure uniform action on the plaster. Scratch coats of one part gypsum and two parts plaster sand by weight, with sufficient water for a consistent, workable mix were then applied. Good keys and bond were obtained. After hardening, finish coats of one part plaster to three parts sand by weight were applied and troweled to give a uniform thickness of specimen approximating 1 in. Drying out was retarded until complete set was assured, after which the panel was permitted to dry for one week before testing. Figure 4 shows a wood lath specimen.

Test Results

Deformation was applied in small increments as a means of identifying the specific instant of cracking, because it was correctly anticipated that audible and visible evidence would not be reliable.

The results for the neat plaster specimen, shown in Fig. 5, are recorded in Fig. 6. The three sets of points up to the 900-lb load are separate runs prior to the final test. The cracking modulus of this specimen is 0.0011.

The cracking moduli of wood lath panels Nos. 1, 3, and 4 are 0.00098, 0.00112, and 0.00093, respectively. The data are shown graphically by Fig. 7. (Panel No. 2 was inadvertently damaged.)

The cracking moduli of metal lath panels Nos. 1, 2, 3, and 4 are 0.00093, 0.00099, 0.00080, and 0.00090, respectively. (See Fig. 8.)

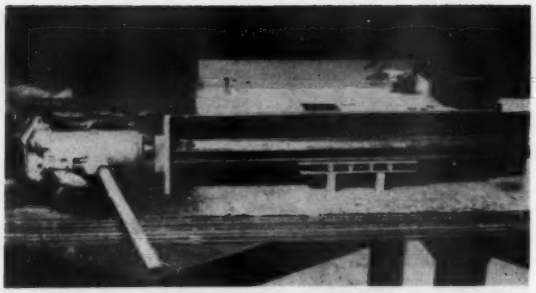


FIG. 3. VIEW OF ROLLERS AND HYDRAULIC JACK APPLYING LATERAL FORCE

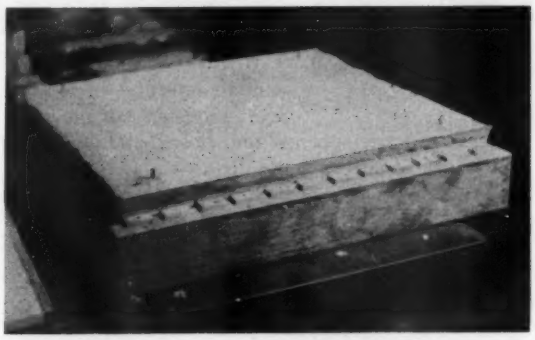


FIG. 4. PLASTER PANEL WITH SECOND COAT

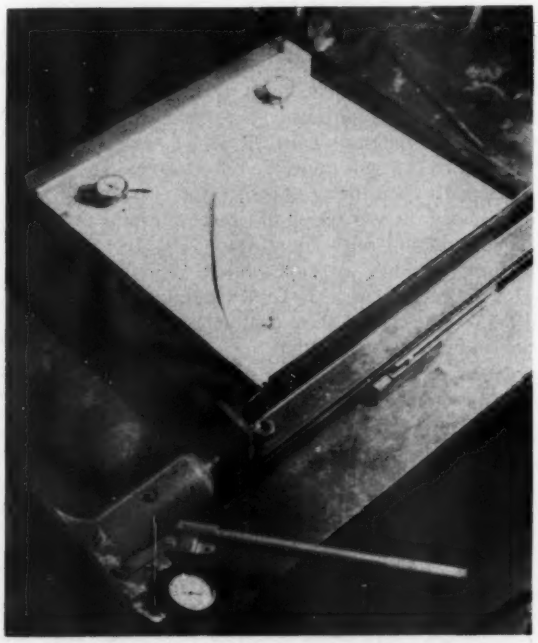


FIG. 5. TYPICAL DIAGONAL TENSION CRACK

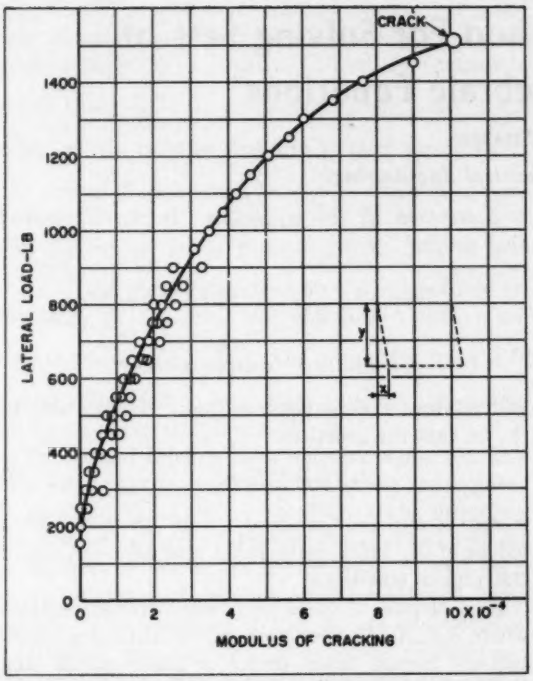


FIG. 6. ANGULAR DEFORMATION CURVE FOR NEAT PLASTER

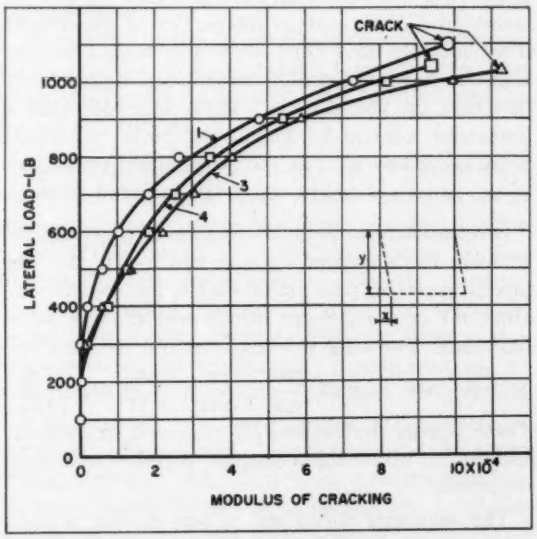


FIG. 7. ANGULAR DEFORMATION CURVE FOR WOOD LATH PANELS

For the eight test specimens the average cracking modulus is 0.00095.

After cracking, the back of each specimen was examined for local effects and it was found in all cases that the cracks extended through and there was no

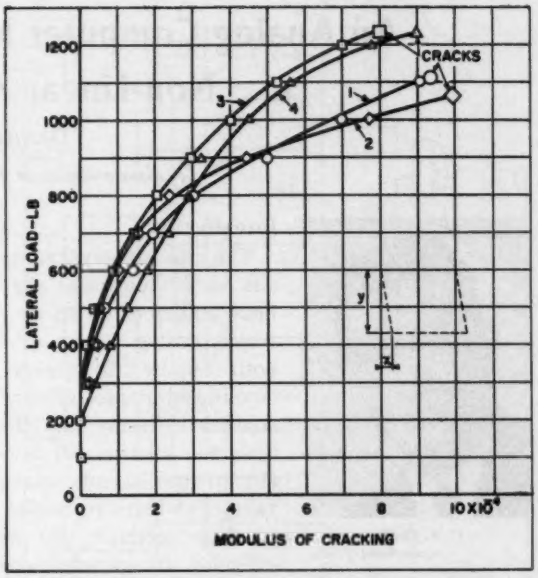


FIG. 8. ANGULAR DEFORMATION CURVE FOR METAL LATH PANELS

shearing of the keys. Also, each specimen was rotated through 90° and loaded again, causing the initial crack to close and a new diagonal tension crack to form at about half the initial load. No deformation readings were taken because the gage points were no longer accurate.

Conclusion

The results of this exploratory study suggest three tentative conclusions that may be substantiated by more extensive investigation.

1. Diagonal tension cracking of gypsum plaster can serve as a criterion in measuring the magnitude and direction of skewing or shear deformation. The concept of the cracking modulus appears to be valid and is supported by a consistent relationship within the limit of cracking.
2. The cracking modulus of both neat and sanded gypsum plaster is determined by the gypsum provided that the mixture is uniform and homogeneous. The integrity of the material is entirely dependent on the gypsum matrix in which the aggregate is imbedded. It appears to be independent of the lath base.
3. The cracking modulus of gypsum and sanded gypsum plasters approximates 0.001. The simple rule for calculating the amount of skewing of an 8-ft plastered wall in which diagonal tension cracks have formed is: $0.001(96) = 0.096$ in. of differential lateral displacement between the ceiling and floor diaphragms, plus the sum of the widths of the open cracks measured in a horizontal direction.

An Analog Computer Method For Solving Sets of Non-Linear Algebraic Equations*

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Introduction

The two principal methods for solving linear algebraic equations on an electronic analog computer[1,2] both require, in general, considerable preliminary analysis to insure that the computer solution will have the proper steady-state value. Furthermore, neither of these methods can be extended to include non-linear equations without making the question of stability more uncertain.

No general analytical method for solving non-linear and transcendental algebraic equations is known. Numerical and graphical methods are available for some types of equations, but they are by no means universally applicable. The method described here is a special case of a method recently developed by C. M. Ablow and Georges Brigham at the Boeing Airplane Company. The Ablow-Brigham method allows an analog computer to be used to solve non-linear programming problems.

It would appear that the present method could also be adapted to digital computation since, as a rule, a sufficiently large digital computer can solve any problem that can be solved on an analog computer.

Discussion of the Method

Description of the Method. Given a set of independent algebraic equations,

$$\phi_k(x_i)=0 \qquad \begin{matrix} k\ 1, 2, \ldots n \\ i\ 1, 2, \ldots n \end{matrix} \qquad (1)$$

to be solved on an analog computer, the problem resolves itself into one of defining the x_i as time dependent variables, $X_i(t)$, in such a manner that the new variables approach a set of limiting values which is a solution of the equations. It can be shown† that setting

$$\frac{dX_i}{dt}=p_i\sum_k S_k\frac{\partial\phi_k}{\partial X_i} \qquad \begin{matrix} S_k=-1\ ;\ \phi_k>0 \\ 1\ ;\ \phi_k<0 \end{matrix} \qquad (2)$$

p_i = arbitrary positive constant,

will produce the required solution. It can also be shown that the function

$$f(X_i)=\sum_k S_k\phi_k \qquad (3)$$

is zero if and only if all of the ϕ_k are zero. Thus values of X_i which make $f(X_i)$ zero are solutions of the original equations.

It is helpful to think of a two-variable problem where $f(X_1,X_2)$ is a function represented as a mountainous terrain lying under a plane which just touches the tops of some of the mountains. These points are the solutions, while X_1 and X_2 are the coordinates of a point on the surface of the terrain. The variables have been defined in such a manner that the point represented moves only in an upward direction on the surface. Thus, in order that a particular solution be found, the initial conditions must be picked so that the point starts on a slope of the mountain whose top is the required solution.

Mechanization. A block diagram of a generalized problem in two variables is shown in Fig. 1. The blocks whose outputs are labeled ϕ_1 and ϕ_2 are combinations of components which will produce these functions. The same is true of the four blocks whose outputs are labeled $\frac{\partial\phi_1}{\partial X_1}$, $\frac{\partial\phi_1}{\partial X_2}$, $\frac{\partial\phi_2}{\partial X_1}$ and $\frac{\partial\phi_2}{\partial X_2}$. These partial derivatives are obtained analytically and are set up on the computer, together with their negatives.

The switching functions, S_1 and S_2, are realized on the computer by using polarized, double-throw relays. The diagram shows that the output ϕ_1 drives a very high-gain amplifier whose output drives a relay. This amplifier will go to its negative limit whenever its input, which is a voltage representing ϕ_1, is positive, and to its positive limit when ϕ_1 is

*Condensed and arranged by the author from his thesis submitted for the degree of M.S. in Electrical Engineering, 1955. Mr. Shafer is in the Mathematical Service Unit of the Physical Research Staff at the Boeing Airplane Company.

†Proof is given in Appendix A of the author's original thesis.

negative. The relay will thus be in the normal closed position when ϕ_1 is positive and in the normal open position when ϕ_1 is negative. From the manner in which the $\pm\frac{\partial\phi_1}{\partial X_1}$ are connected to the poles of the relay, it can be seen that the voltage appearing at the arm of the relay will be $+\frac{\partial\phi_1}{\partial X_1}$ when ϕ_1 is positive and $-\frac{\partial\phi_1}{\partial X_1}$ when ϕ_1 is negative. Taking into account the sign change that occurs in the integrating amplifier, the setup just described is the realization of the term $S_1\frac{\partial\phi_1}{\partial X_1}$. The arm of the relay is of course connected to one of the inputs of the integrating amplifier that forms X_1.

Relays and integrating amplifiers connected in a manner similar to that described above are required to generate the X_i in any problem to be solved by the present method. However, the kind and amount of equipment needed to produce the ϕ_k and their partial derivatives depends on the equations being solved. For instance, if the ϕ_k are polynomials, multipliers are required to generate powers and products of the variables, and amplifiers are needed to sum the terms, both for the ϕ_k and their partial derivatives.

In case one of the ϕ's should contain an arbitrary function of one of the variables, function generators would be needed to generate the function and its partial derivatives.

Operating Procedure. Once a set of equations is scaled and set up on the computer, the process of finding all the roots in the region covered by the range of the computer variables is more or less mechanical. The initial conditions are set to some convenient values, usually all zero, and the computer is switched to operate. The computation proceeds until all the variables X_i remain constant at some new values. The amplifiers generating the ϕ_k are all scanned. If their outputs are all zero, a solution has been found. If one or more of the ϕ_k are not equal to zero, the values of X_i are not a solution. However, these values are noted and the computer is returned to the initial condition.

New initial conditions for the X_i are now set up, each somewhat larger than the value attained in the first trial solution. The computer is again switched to operate and the final values of the variables and the ϕ_k are noted. It will be found either that another false solution identical with the first has been obtained, that a false solution different from the first has been obtained, or that the result was a valid solution. In any case the same procedure is repeated. New initial conditions, each larger than the last are chosen, the problem is run again, and the ϕ_k are monitored to check the validity of the results.

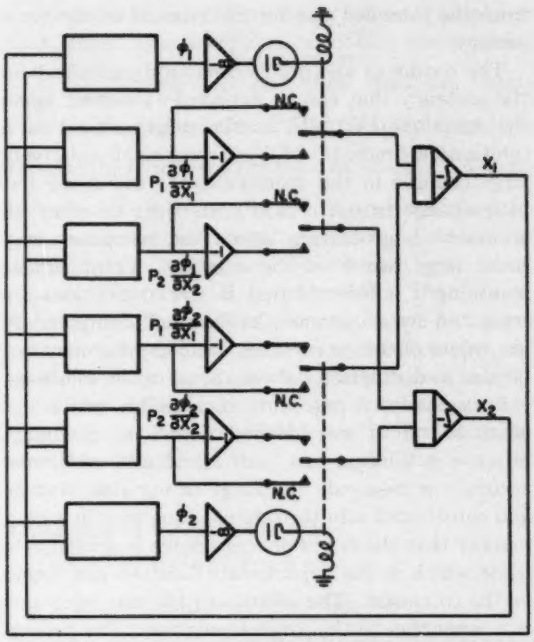


FIG. 1. DIAGRAM OF A GENERALIZED PROBLEM IN TWO VARIABLES

In this manner, all of the solutions lying in the region for which the computer variables have been scaled can probably be found. It may turn out that all the solutions are not produced by this procedure. A systematic search for a starting point of a path that leads to the missing solution must then be made.

Accuracy. The accuracy of any analog computation depends on the problem being solved and on the tolerances of the computer components and their frequency characteristics. For instance, the accuracy with which an amplifier performs the operation of summation depends on the departures from nominal values in the input and feedback resistors and the frequency response of the amplifier.[3] All of the other components, such as servos, multipliers, and function generators, perform their functions with measurable errors. The magnitudes of the errors for any single operation (that is, summation, function generation, multiplication, etc.) may range from a few hundredths of a percent to as much as several percent.

The effect of errors of this type is that the solutions found are solutions to a problem that differs

from the intended one by the amount of the error present.

The nature of the problem has a direct effect on the accuracy that can be achieved. Consider again the function $f(X_i)$. If, in the neighborhood of a solution the gradient of $f(X_i)$ is very small, relatively large changes in the coordinates X_i will cause but little change in $f(X_i)$. Thus any drift or other inaccuracy in generating ϕ_i on the computer may cause large errors in the solution. From similar reasoning it is inferred that if several solutions are separated by a distance that is small compared to the values of the coordinates, the computer may not be able to distinguish between some of the solutions.

Fortunately, a procedure is available which appears to afford any desired degree of accuracy. Suppose a solution has been found and additional accuracy is required. A change of variable is made and substituted into the original equations in such a manner that the origin of coordinates is shifted to a point which is the approximate solution just found on the computer. The solution of the new equations is a correction to the original solution. The process may be repeated as often as necessary to get the required accuracy. The accuracy at any time can be checked by substituting the approximate solution into the original equations. The change of coordinates tends to linearize the equations, which greatly improves the accuracy of the computations. Furthermore, it has been shown* that the error, in terms of the difference in the coordinates of the approximate and the actual solution, after any number of corrections, is only the error in the last correction. Thus, even though the first try is quite crude, accurate solutions can still be obtained.

The drawback to this procedure is, of course, that it can become quite tedious if the number of solutions is large and one or more corrections must be made to each of them. However, an investigation of the effects on the solutions of a few parameter changes in the original set of equations will take very little more time than the solution of a single set of equations.

Example

Three sample problems have been solved. All are quartics with complex roots. The choice of this type of equation for the examples was suggested by the availability of the non-linear equipment required, i.e., servo multipliers, and the fact that accurate solutions could be obtained by other means for a check. One problem will be described here in detail:

$$z^4+80.08z^3+3206z^2+128{,}128z+2{,}560{,}000=0. \quad (4)$$

The scaling and computer equations will be shown for Eq. 4. Separating the real and imaginary parts and equating each to zero gives:

$$\begin{aligned}\phi_1=&X_1^4+80.08X_1^3+3{,}206X_1^2+128{,}128X_1\\&-240.24X_1X_2^2-6X_1^2X_2^2\\&-3{,}206X_2^2+X_2^4+2{,}560{,}000\,,\end{aligned} \quad (5)$$

$$\begin{aligned}\phi_2=&4X_1^3+240.24X_1^2+6{,}412X_1-4X_1X_2^2\\&-80.08X_2^2+128{,}128\,,\end{aligned} \quad (6)$$

where

$$\begin{aligned}f(z)&=u+iv\\&=\phi_1+iX_2\phi_2\\\phi_2&=v/X_2\\z&=X_1+iX_2\,.\end{aligned}$$

Note that by solving for v/X_2 instead of v, a set of equations in the variables X_1 and X_2^2 is obtained. This reduces the number of multiplications required and assures that one of the variables will always be positive at the solutions. It also reduces the number of solutions from four to two in cases where X_2 equal to zero is not a solution.

The Boeing Electronic Analog Computer, on which these equations were solved, has a working range of ± 50 volts. The variables were therefore scaled to come within this range. To accomplish this, the following scale factors in Table I were used.

TABLE I

Original Variable	Estimated Maximum	Computer Variable	Scaling Equation
X_1	50	$\overline{X}$	$1\overline{X}=X_1$
X_1^2	2,500	η_2	$50\eta_2=X_1^2$
X_1^3	125,000	η_3	$2{,}500\eta_3=X_1^3$
X_1^4	6,250,000	η_4	$125{,}000\eta_4=X_1^4$
X_2^2	2,500	γ_2	$50\gamma_2=X_2^2$
X_2^4	6,250,000	γ_4	$125{,}000\gamma_4=X_2^4$
$X_1X_2^2$	*125,000	$\overline{X\gamma_2}$	$2{,}500\overline{X\gamma_2}=X_1X_2^2$
$X_1^2X_2^2$	6,250,000	$\overline{\eta_2\gamma_2}$	$125{,}000\overline{\eta_2\gamma_2}=X_1^2X_2^2$

The following relations are obtained from the scaling equations in the table:

$$\begin{aligned}\eta_2&=.02\,(\overline{X}\cdot\overline{X})\\\eta_3&=.02\,(\overline{X}\cdot\eta_2)\\\eta_4&=.02\,(\overline{X}\cdot\eta_3)\\\gamma_4&=.02\,(\gamma_2\cdot\gamma_2)\\\overline{X\gamma_2}&=.02\,(\overline{X}\cdot\gamma_2)\\\overline{\eta_2\gamma_2}&=.02\,(\eta_2\cdot\gamma_2)\end{aligned}$$

*In Appendix B of the author's original thesis.

The following partial derivatives are used to find $\frac{\partial \phi_1}{\partial X_1}$ etc., directly in terms of the computer variables, thus saving a great deal of hand calculation:

$$\frac{\partial \eta_2}{\partial \overline{X}} = .04(\overline{X}) \qquad \frac{\partial(\overline{X\gamma_2})}{\partial \overline{X}} = .02(\gamma_2) \qquad \frac{\partial \gamma_4}{\partial \gamma_2} = .04(\gamma_2)$$

$$\frac{\partial \eta_3}{\partial \overline{X}} = .06(\eta_2) \qquad \frac{\partial(\overline{\eta_2\gamma_2})}{\partial \overline{X}} = .04(\overline{X\gamma_2}) \qquad \frac{\partial(\overline{X\gamma_2})}{\partial \gamma_2} = .02(\overline{X})$$

$$\frac{\partial \eta_4}{\partial \overline{X}} = .08(\eta_3) \qquad \frac{\partial(\overline{\eta_2\gamma_2})}{\partial \gamma_2} = .02(\eta_2)$$

The new variables and scale factors given in the table are substituted into the equations and the partial derivatives are calculated. The result is the set of computer equations shown below.

$$\frac{-u}{730\times 10^3} = -\bar{u} = -\left[\frac{\eta_4}{6} + .2669\eta_3 + .2137\eta_2 + .1708\overline{X} - .8008\overline{X\gamma_2} - \overline{\eta_2\gamma_2} - .2137\gamma_2 + .6827(50)\right],$$

$$\frac{-v/X_2}{10^4} = -\bar{v} = -[\eta_3 + 1.2012\eta_2 + .6412\overline{X} - \overline{X\gamma_4} - .4004\gamma_2 + .2563(50)],$$

$$-25\frac{\partial \bar{u}}{\partial \overline{X}} = -\left[\frac{\eta_3}{3} + .4004\eta_2 + .2137\overline{X} - .4004\gamma_2 - \overline{X\gamma_2} + .8542\frac{(50)}{10}\right],$$

$$+50\frac{\partial \bar{u}}{\partial \gamma_2} = -\left[.8008X + \eta_2 - \frac{\gamma_2}{3} + .2137\ (+50)\right],$$

$$+50\frac{\partial \bar{v}}{\partial \gamma_2} = -[\overline{X} + .4004\ (+50)], \quad 25\frac{\partial \bar{v}}{\partial \overline{X}} = -\frac{3}{2}50\frac{\partial \bar{u}}{\partial \gamma_2}$$

$$\overline{X} = -\frac{1}{0.5}\int\left[S_u\left(25\frac{\partial \bar{u}}{\partial \overline{X}}\right) + S_v\left(-\frac{3}{2}50\frac{\partial \bar{u}}{\partial \gamma_2}\right)\right]dt,$$

$$-\gamma_2 = -\frac{1}{1}\int\left[S_u\left(50\frac{\partial \bar{u}}{\partial \gamma_2}\right) + S_v\left(50\frac{\partial \bar{v}}{\partial \gamma_2}\right)\right]dt.$$

Advantage is taken of the relation, $\frac{\partial \bar{v}}{\partial \overline{X}} = -3\frac{\partial \bar{u}}{\partial \gamma_2}$, to eliminate two amplifiers otherwise needed to compute $\frac{\partial \bar{v}}{\partial \overline{X}}$ and its negative.

The schematic diagram of Fig. 2 shows how the computer is set up to solve this problem. The similarity to the generalized diagram in Fig. 1 is obvious. In the upper left corner of the diagram are two amplifiers that sum powers and products of the variables to give $-\bar{u}$ and $-\bar{v}$ which are the computer variables representing ϕ_1 and ϕ_2. Immediately below these two amplifiers are six summing amplifiers that form the computer variables representing $\frac{\partial \phi_1}{\partial X_1}$, $\frac{\partial \phi_1}{\partial X_2}$, and $\frac{\partial \phi_2}{\partial X_2}$ and their negatives. Only three of the four partials are formed in this manner because the fourth is a constant times $\frac{\partial \phi_1}{\partial X_2}$. The relays are set up in exactly the manner described for the general problem. On the right hand side of the diagram two servos are shown, each with three potentiometers on its output shaft. These units, together with amplifiers used to isolate the servo potentiometers, form all the required powers and products of the variables. A regulated power supply, shown in the lower center of the diagram as a battery, supplies the constant inputs to the summing amplifiers forming the ϕ's and their partial derivatives.

Discussion of the Example

The actual roots of Eq. 4 are:

$$z = -.04 \pm i\,40; \quad z = -40 \pm i\,.04.$$

The corresponding solutions found on the computer are:

$z = -.18 \pm i\,40.2$; $z = -40.2 \pm i\,8.60$ (first approximation).

A second approximation was made to the second pair of roots of Eq. 4. The change of variables was accomplished by substituting

$$X_1 = -40.2 + X_1' \,;\; X_2^2 = +74 + (X_2')^2$$

into Eqs. 5 and 6. Applying the scale factors

$$.02\overline{X} = X_1' \,;\; 2\gamma_2 = (X_2')^2, \text{ and so on,}$$

gives the following equations to be solved for the second approximation:

$$\bar{u}' = .009(\eta_2) + .05378(\overline{X}) + .07823(\overline{X\gamma_2}) + .03230(\gamma_4) + (-\gamma_2) - 37.973, \tag{7}$$

$$-\bar{v}' = .08977(\eta_2) + .04955(\overline{X\gamma_2}) + (-\gamma_2) + .7672(-\overline{X}) - 29.163. \tag{8}$$

It should be noted that several of the higher order terms have been left out because their coefficients became negligibly small. In fact, retaining only the linear terms would have been a good approximation. The computer solutions for these equations were found to be:

$$X_1' = .274 \,;\; (X_2')^2 = -78.$$

The corrected solutions are: $X_1 = -39.93$; $X_2^2 = -4$. A negative value for X_2^2 is, of course, impossible.

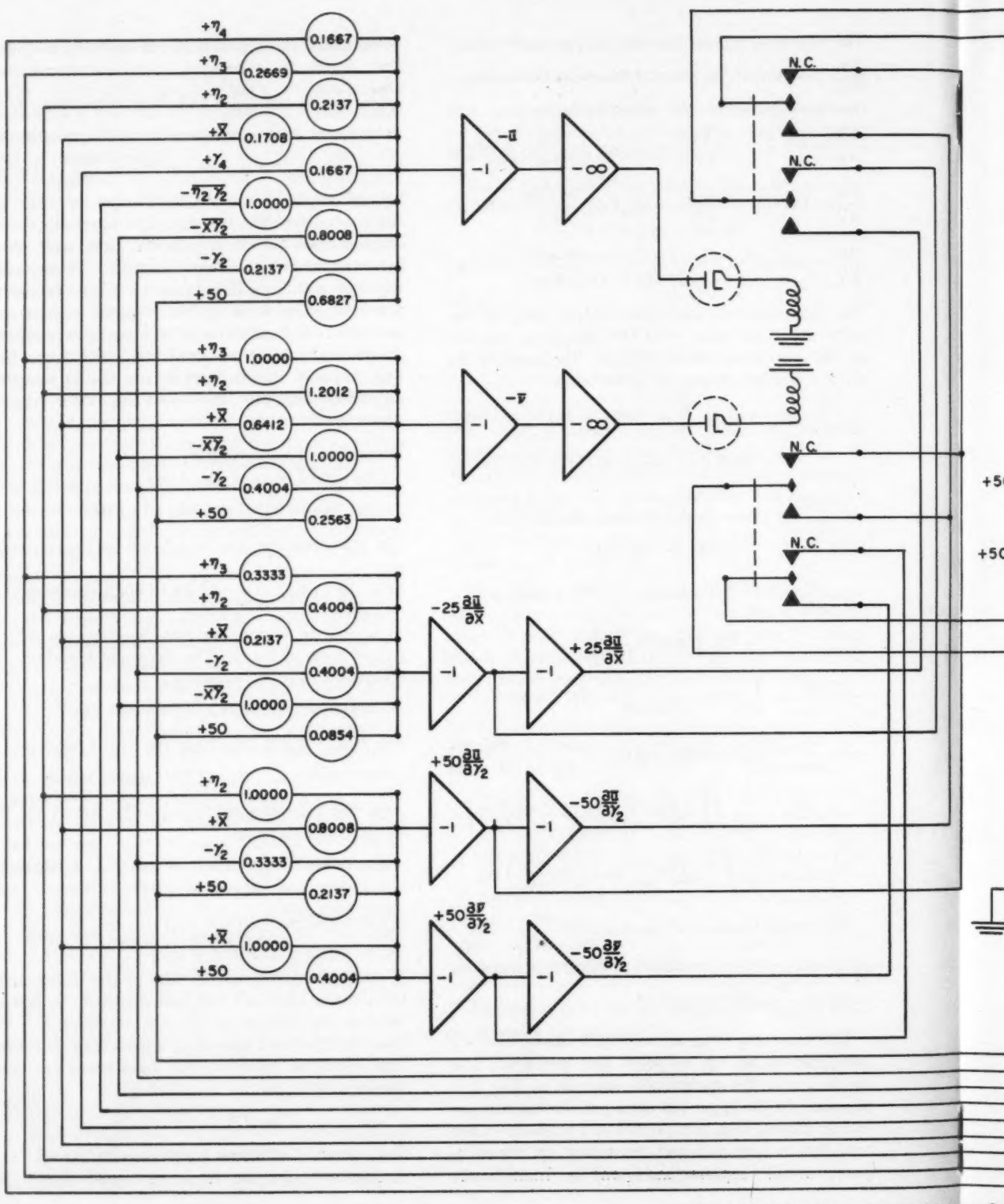
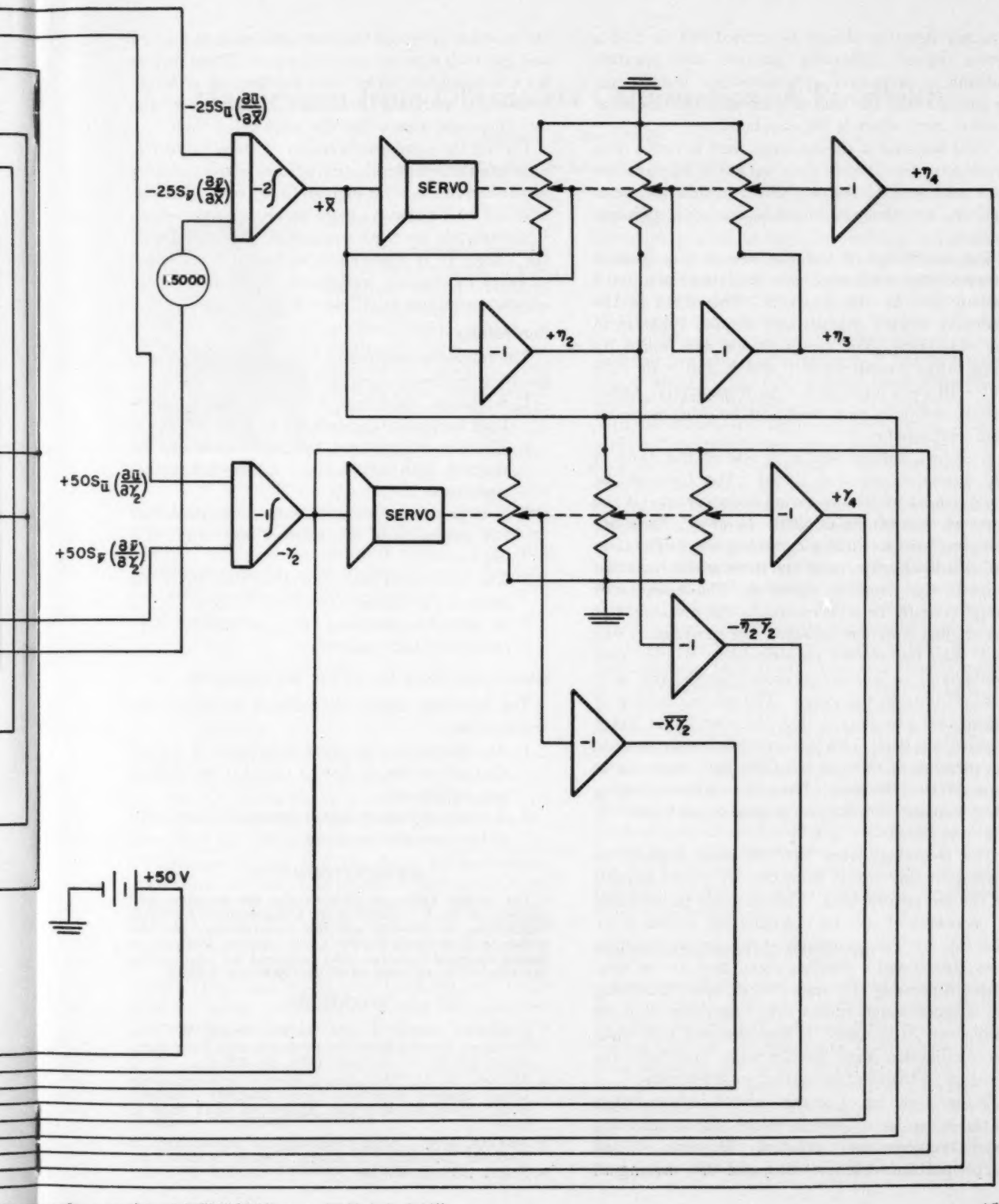


FIG. 2. SCHEMATIC DIAGRAM OF COMPUTER SE


$-25S_{\bar{u}}\left(\frac{\partial \bar{u}}{\partial \bar{x}}\right)$
$-25S_{\bar{p}}\left(\frac{\partial \bar{p}}{\partial \bar{x}}\right)$
-2∫
$+\bar{x}$
SERVO
-1
$+\eta_4$
1.5000
-1
$+\eta_2$
-1
$+\eta_3$
$+50S_{\bar{u}}\left(\frac{\partial \bar{u}}{\partial \bar{y}_2}\right)$
$+50S_{\bar{p}}\left(\frac{\partial \bar{p}}{\partial \bar{y}_2}\right)$
-1∫
$-\bar{y}_2$
SERVO
-1
$+\gamma_4$
-1
$-\overline{\eta_2 \gamma_2}$
-1
$-\overline{x \gamma_2}$
+50 V

Another iteration should be carried out to find a better value. Obtaining positive and negative answers on successive approximations would seem to indicate that the true solution is in the neighborhood of zero, which is the case here.

Time histories of the solutions were recorded on a brush recorder. Steady-state values of the variables were read on a 0.5 per cent direct-current voltmeter since the recordings could not be read with sufficient accuracy.

The recordings of the solutions of Eq. 4 show characteristic small amplitude oscillations of $\bar{u}$ and $\bar{v}$ around zero at the solutions. The effect of the switching when $\bar{v}$ changes sign is quite apparent in the $-\gamma_2$ trace. The two solutions were found by using initial conditions of 0 and 0, and -20 volts and -10 volts for $\overline{X}$ and $-\gamma_3$, respectively. Other initial conditions were tried, but no other solutions were forthcoming.

A second approximation to one of the roots of Eq. 4 was set up and solved. The form of the equations set up for the second approximation is the same as that of the original. However, there are two peculiarities. First, the problem was deliberately scaled so that only one of the roots would lie in the range of the computer variables. The second root would actually be a correction to the other root of the original equation; however, the substitution was such that the second approximation to this root would likely be no more accurate than the first, so it was left outside the range. The second feature of the revised equation is that the root found has a positive real part. This is worth mentioning because the presence of roots in the right half plane causes no stability difficulties. The effect of the switching when $\bar{v}$ crosses zero is quite evident in both the $-\overline{X}$ and $-\gamma_2$ traces.

The recordings show that the time required to reach solutions varied from two to twelve seconds for the sample problems. This time can be increased or decreased at will by changing the values of p_i. (See Eq. 2.) The recordings of the sample solutions show that $\bar{u}$ and $\bar{v}$ oscillate about zero at the solutions. Increasing the values of p_i, thus decreasing the solution time, causes the magnitude of these oscillations to increase. It was observed that when the oscillations were greater than one volt, the accuracy of the solution started to deteriorate.

Study of the proof of the method indicates that all the p_i can have different values without affecting the convergence to a solution. However, in the sample problems tried, it was found that making all the p_i equal produced the least oscillation in $\bar{u}$ and $\bar{v}$ and gave the most accurate solutions. These factors are not completely understood, but they are probably connected with the frequency response of the amplifiers and servos and the relay delay time.

During the computer solution of these problems, inaccuracies in multiplication of some of the variables were observed to be as high as 10 per cent. This was believed to be due to worn servo potentiometers. Unfortunately no other equipment was available at the time. It is reasonable to believe that, with properly functioning equipment, considerably more accurate solutions would be obtained.

Conclusions

The following conclusions have been reached as a result of the foregoing investigation:

1. Sufficient conditions for obtaining solutions have been stated and shown to exist.
2. The circuits required by the method can be realized with conventional analog computing equipment.
3. A large amount of equipment is required, but the generality of the method may offset this objection.
4. The parameters that control the stability of the computer setup have not been isolated.
5. In all of the problems tried, no stability difficulties were encountered.

Recommendations for Future Investigations

The following topics are suitable for future investigations:

1. An examination of other definitions of dX_i/dt that satisfy the conditions on $f(X_i)$ but require less equipment.
2. A study of factors that determine the stability of the computer solutions.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance and guidance of Dr. L. J. Lewis of the Department of Electrical Engineering in carrying out this investigation. He also wishes to give credit to Dr. C. M. Ablow, formerly of Boeing Airplane Company, who conceived the original idea that resulted in the thesis on which this article is based.

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Magnesium from Olivine *via* Chlorination: A Possibility

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Introduction

In the Cascade foothills about twenty miles northeast of Mount Vernon, Washington, is a large body of rock which presents a challenge of ever-increasing interest to chemical and metallurgical engineers. It is a mass of high-grade dunite, or olivine, about ten miles long and three miles wide, making up the Sisters Mountains, from their base at about 3,000 feet elevation above sea level to the summits between 6,000 and 6,700 feet elevation. Chemical analyses of numerous samples from this dunite body have shown a large part of it to have the following average chemical composition:

MgO	49.2%
FeO	7.2%
Al_2O_3, MnO, CoO	2.0%
CaO	0.2%
SiO_2	41.8%
Ignition	0.2%

Not included in the above analysis is chromite, $Fe(CrO_2)_2$, which occurs as small black crystals distributed throughout the light green olivine mass. The amount of chromite present varies greatly but averages about one per cent.

It is easy to see that this large olivine deposit would be a very tempting source of magnesium metal if an economic means of processing the mineral could be found. Interest in olivine has also been markedly stimulated during the last year or two by the building of high-speed logging roads on the flanks of the Sisters Mountains, which have made the area much more accessible. Some olivine is now being quarried for foundry sand and other refractory uses not the subject of this paper. Delivered cost of quarry-run rock at the Hamilton, Washington, railhead is about $5.00 per ton.

Chemical Properties of Olivine

Olivine is a chemically reactive material. Rain water containing dissolved carbon dioxide removes the magnesium content as soluble bicarbonate and the silica content probably as colloidal silicic acid. Underground waters hydrate and alter olivine readily to serpentine and talc, which is one reason deposits of high-grade dunite are quite rare. A second large Washington deposit of olivine on Cypress Island in the San Juan group, for example, has undergone considerable hydrothermal alteration. It has an ignition loss of about 10 per cent and, for most purposes, is inferior to rock from the Sisters Mountains.

In the laboratory, dilute solutions of all mineral acids will completely decompose finely divided olivine in a short time. Unfortunately the magnesium and iron salts formed in the decomposition reaction cannot easily be separated from the simultaneously produced gelatinous silicic acid. Olivine does not react with hydrogen at normal or elevated temperatures or with gaseous hydrogen chloride at elevated temperatures, but is readily reduced by carbon to elemental silicon and free magnesium at electric furnace temperatures. Both the magnesium and silicon produced have high vapor pressures in this temperature range and leave the reaction zone simultaneously with carbon monoxide produced in the reduction. As soon as a zone of lower temperature is reached, reversal of the reduction reactions is rapid and complete.

Olivine reacts readily with chlorine in the presence of a reducing agent at elevated temperatures. In general, the chemical reactivity of olivine is the same as that of magnesium oxide, and the same reaction products are obtained with a given reagent as would be obtained with pure magnesium oxide. Of course, reaction products of the magnesium oxide, iron oxide, and silica contents of olivine will usually be obtained as an intimate mixture.

Preparation of Metallic Magnesium

Commercial Processes. All successful processes for the commercial preparation of metallic magnesium to date have started with either magnesium oxide, magnesium chloride, or substances from which one of these could be very easily prepared. During World War II, processes were in commercial operation for metal production which involved oxide reduction with ferrosilicon, oxide reduction with carbon, oxide reduction with carbides, and electrolysis of fused magnesium chloride produced both by chlorination

of the oxide and by chemical treatment of sea water. Significantly, although countless hours had been expended by some very brilliant investigators in efforts to make the various processes as efficient as possible, only the one based on electrolysis of fused magnesium chloride produced from sea water remained in operation after the war ended and normal economic conditions returned. In view of the similarity between the chemical reactivity of magnesium oxide and that of olivine, the conclusion is inevitable that if a process for preparing magnesium metal from olivine could be found that would be able to compete with the seawater process, such a process would employ magnesium chloride as an intermediate. A means would have to be found of preparing pure anhydrous magnesium chloride more economically than is possible from sea water, or of producing a grade of magnesium chloride sufficiently better to offset any added cost of production. Attainment of this goal would represent a very considerable achievement, as the sea is an unlimited source of magnesium chloride, and the Dow Chemical Company operates its process very efficiently.[1]

Previous Work on Olivine. During and since World War II, olivine has held the attention of many investigators as a possible source of magnesium chloride. Ketzlach,[2] Pawel,[3,4] Houston,[5] and, more recently, Gee and Huff,[6] have employed various acid leaching techniques. These techniques have been successful in solving the problems of obtaining complete reaction and separation of magnesium chloride from residual silicic acid, but require much costly equipment. More important, when processing is complete the magnesium chloride product is hydrated and would have to be subjected to the same expensive dehydration process as magnesium chloride from sea water before it could be used in electrolytic cells. Commercial application of acid leaching techniques is not considered likely.

Direct chlorination has been attempted by Carl,[7] the Tennessee Valley Authority,[8] Hansen,[8] and Brooks,[9] among others, in an effort to avoid the hydration problem. All of these investigators operated in the temperature range 800° to 1000° C, and all reported substantial conversion. Unfortunately, the liquid magnesium chloride and silica residue produced were present in such amounts that a pasty mass formed which was difficult to handle and from which separation of magnesium chloride was impossible without resorting to a water leach. Presence of the silica residue-liquid chloride layer on the surface of partially reacted mineral particles also caused the reaction to go to completion at an impractically slow rate.

Bengtson and Ebright[10] were the first to chlorinate at a temperature high enough to vaporize all metal chlorides formed, thus at once effecting separation from the residue and making possible effective contact between chlorine and the unreacted particle surface during the entire chlorination.

Magnesia conversions of more than 90 per cent were obtained, but chlorination at 1350° C imposed many problems. Graphite was believed at the time to be the only material of construction available which would not react with chlorine at 1350° C, but gases permeate it readily at high temperatures, and a strongly reducing atmosphere will necessarily prevail within equipment constructed from it. Satisfactory material balances could not be obtained for the chlorination runs because some of the magnesium chloride, silica, and some elemental chlorine passed through the walls of the apparatus in the gas phase and were lost. Exhaust gases bearing magnesium chloride were shock-chilled on leaving the apparatus, resulting in formation of a magnesium chloride dust that was difficult to work with.

Chlorination Reactions

Mechanism. Ebright's and Bengtson's experimental work indicated that a detailed study of the chemistry of olivine chlorination, including energy relationships, would be necessary to determine a profitable approach for further work. No study of the mechanism of olivine chlorination is reported in the literature, but, considering the mechanism to be essentially the same as that reported by Doerner and Holbrook,[11] Pidgeon and Phillips,[12] and others, for the chlorination of magnesium oxide, the following equilibria are believed to exist during the chlorination of olivine near the normal boiling temperature of magnesium chloride:

$$\tfrac{1}{2}\ Mg_2\ SiO_4 + Cl_2 \rightleftarrows MgCl_2 + \tfrac{1}{2}\ SiO_2 + \tfrac{1}{2}\ O_2, \quad (1)$$

$$SiO_2 + Cl_2 \rightleftarrows SiOCl_2 + \tfrac{1}{2}\ O_2, \quad (2)$$

$$SiOCl_2 + Cl_2 \rightleftarrows SiCl_4 + \tfrac{1}{2}\ O_2. \quad (3)$$

If carbon were present as an oxygen acceptor, additional equilibria would be

$$C + \tfrac{1}{2}\ O_2 \rightleftarrows CO, \quad (4)$$

$$CO + \tfrac{1}{2}\ O_2 \rightleftarrows CO_2, \quad (5)$$

$$CO_2 + C \rightleftarrows 2CO. \quad (6)$$

Fortunately the eutectic melting temperature for silica-magnesium oxide is well above 1350° C, so it was unnecessary to be concerned with the formation of a liquid silicate phase, regardless of the relative rates of chlorination of magnesium oxide and silica.

Thermodynamic Study. Considering the foregoing equations to represent completely the equilibria in a system comprising olivine, chlorine, and a carbonaceous reducing agent, the free energy change and heat

of reaction for various combinations of the above reactions were calculated for temperatures near the normal boiling point of magnesium chloride, assuming any chloride produced to be in the gas phase. The calculations showed that olivine chlorination by the same type of reaction mechanism as for magnesium oxide chlorination is thermodynamically feasible. An appreciable partial pressure of free oxygen would be expected to exist in equilibrium with olivine mineral and free chlorine, but this partial pressure would not be high enough to allow the chlorination to proceed to completion unless some means were provided to remove the oxygen. However, the chlorination could be expected to proceed virtually to completion if carbon or CO were used as oxygen acceptor. The use of HCl as the chlorinating agent and for removal of oxygen as water was not found to be thermodynamically feasible, or in practice possible. It was found not only that silica could be expected to chlorinate along with the magnesium content of olivine, but also that any silicon tetrachloride formed would itself act as a chlorinating agent to chlorinate the magnesium content of olivine with the re-formation of silica. The methods of thermodynamics do not, of course, permit determination of the time rates of any of these chemical reactions.

The amount of heat energy liberated in the chlorination reaction was found to vary greatly, depending on whether carbon monoxide or carbon was used as oxygen acceptor, and if carbon was used, upon the amount used. The reaction of greatest interest in this regard was

$$Mg_2SiO_4\,(c) + 2CO(g) + 2Cl_2(g) \rightleftarrows 2MgCl_2(g) + SiO_2(c) + 2CO_2(g), \quad (7)$$

because the heat-energy yield was highest and could conceivably be great enough to maintain a properly designed chlorinator at the high temperature required for chlorination. One gram molecular weight of magnesium silicate chlorinating according to Eq. 7 was calculated to yield 49.8 kilocalories at 1400° C.

Objectives of the Present Work

The reaction represented by Eq. 7 appears to be best suited for possible commercial magnesium chloride production.[13] Oxygen acceptor and chlorine can be supplied intimately mixed in correct proportions; local excessive concentrations of either cannot occur. Most important, it is possible to envision a large-scale fluidized-solids chlorination unit similar to that shown in Fig. 1. Such a unit is now used industrially for calcination of limestone.[14] Fresh mineral of appropriate particle-size range would enter continuously at the top and be fluidized by the ascending gases consisting of essentially equimolal proportions of carbon monoxide and chlorine at the bottom of the unit and gaseous reaction products at the top

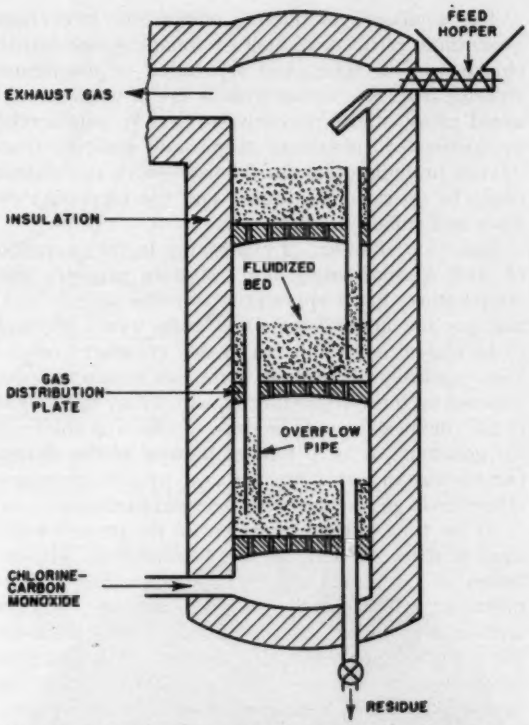

FIG. 1. DIAGRAMMATIC LONGITUDINAL CROSS SECTION OF LARGE-SCALE THREE-BED CHLORINATOR EMPLOYING FLUIDIZED SOLIDS

of the unit. Silica residue would leave the bottom of the unit continuously. The chlorination unit would operate at a temperature such that the vapor pressure of liquid magnesium chloride would always be greater than the stoichiometrically possible partial pressure of magnesium chloride. Such operation should effect continuous separation of magnesium chloride from silica residue. Mineral, chlorinating agent, residue, and desired reaction products would all be transported into, through, and out of the reaction zone continuously without employment of moving equipment. This would simplify equipment construction and avoid several difficult problems, such as the maintenance of rotating gas seals at high temperatures.

Some silicon halides would be unavoidably formed in the lower part of the chlorinating unit where the chlorine-carbon monoxide concentration would be high. Silicon halides formed in the lower part of the unit would be expected to react with fresh mineral in the upper part of the chlorination unit to produce magnesium chloride and more silica. No silicon halides would be forming in the upper part of the unit because of low chlorine-carbon monoxide concentrations, and it is possible that the net chlorine conversion to silicon halides might be kept very small.

The avoidance of moving equipment, large heat generation, recovery of at least some chlorine lost to chlorination of silica, and separation of magnesum chloride from the residue without use of water, would avoid many of the previous barriers to commercial production of anhydrous magnesium chloride from olivine, providing that the fluidized-solids chlorinator could be operated as desired and the reaction took place at a sufficiently high rate.

Many variables are of importance in the operation of such a chlorinating unit. System pressure and temperature, gas composition, mineral particle size, and gas and mineral mass flow rates would all have to be chosen to permit reasonably complete conversion, especially of chlorine, in the gas stream. Superimposed on these requirements, which may be thought of as "chemical," would be those of choosing chlorinator geometry so as to fluidize mineral of the chosen particle size in such a manner as to provide necessary efficiency of gas contact with the solid particles.

At the time of commencement of the present work most of these variables were undetermined. The reaction of Eq. 7 had not even been verified experimentally in chemically inert equipment. Almost nothing was known about fluidization variables for the conditions under which a chlorinator of this type would operate. It would be possible to study the chemical variables mentioned above in a reactor employing a comparatively simple fixed bed, so the decision was made to use a fixed bed in the present work, deferring study of chlorination in a fluidized bed until such time as results obtained from fixed-bed studies indicated that chlorination of olivine in a fluidized bed might be promising. Accordingly, experimental work was undertaken with the following specific objectives:

1. To verify occurrence of the reaction indicated by Eq. 7 in chemically inert equipment. Previous investigators working near the normal boiling point of magnesium chloride had always used graphite equipment.
2. To determine the rate at which the reaction of Eq. 7 proceeds under various conditions of temperature, degree of conversion of a particle, particle size, and chlorine-carbon monoxide concentration.
3. To obtain information as to whether or not the silica residue would in fact chlorinate.
4. To test quartz to determine its suitability as a refractory material of construction under the severely corrosive conditions to be encountered.
5. To correlate the above information to determine whether it might be possible to carry out chlorination of olivine in a fluidized bed.

To these ends a series of 18 runs were made and analyzed. All runs were made in the fused quartz chlorinator shown in Fig. 2. A small globar furnace was used to attain the necessary temperatures.

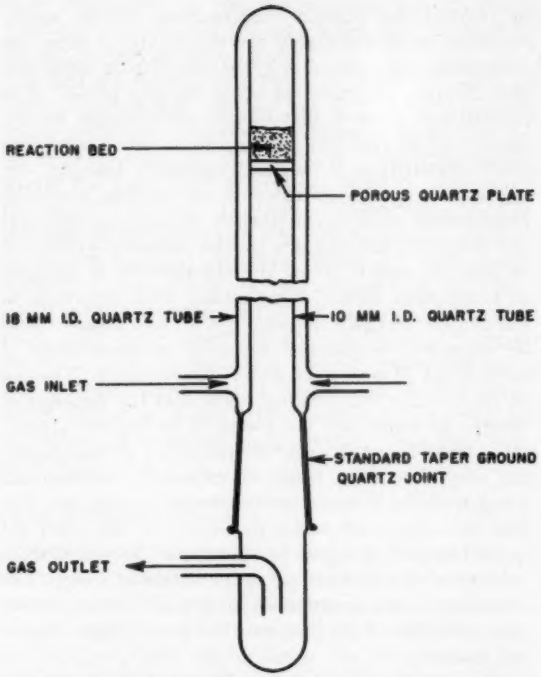

FIG. 2. DIAGRAMMATIC CROSS SECTION OF FUSED QUARTZ CHLORINATOR USED FOR TESTS

Experimental Results

General Observations. Results for all runs are shown in Table I. Curves showing mole fraction chlorine in the exhaust gas before chloride condensation as a function of the number of theoretical requirements of chlorine supplied are shown in Fig. 3. One theoretical requirement of chlorine is defined to be 0.0143 gram moles, or the amount of chlorine theoretically required to completely chlorinate the magnesium and iron content of the 1.00-gram olivine samples used, to magnesium chloride and ferric chloride. Photomicrographs of residues are shown in Figs. 4 and 5. In all runs in which significant conversion occurred, the surface of the partially decomposed mineral particles is covered with a layer of very small, intergrown quartz crystals. Figure 5 shows well-developed quartz crystal structure on residue particles of Run No. 14. Olivine particles only slightly decomposed are shown in Fig. 4.

The exhaust gases of each run, after condensation and removal of metal chlorides, were passed through a water trap in which any silicon halides present would be hydrolyzed to silica and hydrochloric acid. The visual estimation of the presence of silicon halides shown in Table I is based upon observance of the white silica deposit. Titration of the hydrochloric acid in the water trap showed that in no case did more than 15 per cent of the silica content of the

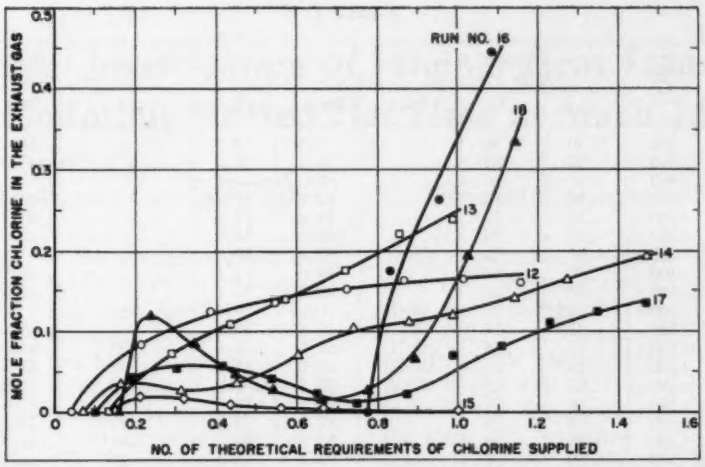

FIG. 3. MOLE FRACTION CHLORINE IN THE EXHAUST GAS AS A FUNCTION OF THE NUMBER OF THEORETICAL REQUIREMENTS OF CHLORINE SUPPLIED

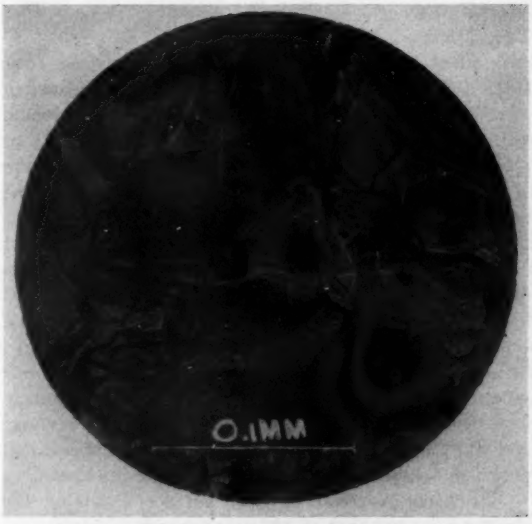

FIG. 4. PHOTOMICROGRAPH SHOWING VERY SLIGHTLY DECOMPOSED MINERAL PARTICLES OF RUN NO. 1
Note that the particles are nearly transparent and show only a trace of fungus-like residue.

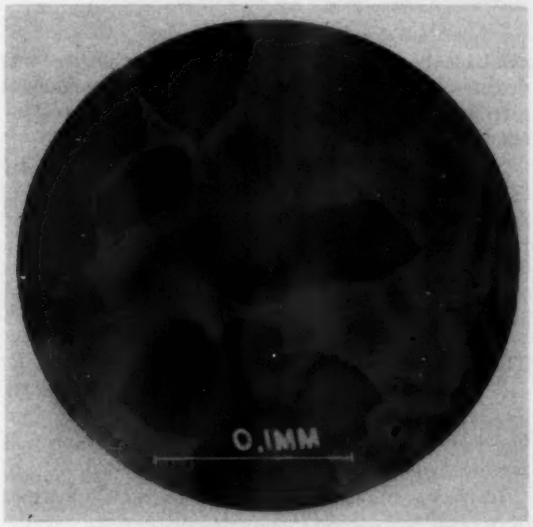

FIG. 5. PHOTOMICROGRAPH SHOWING RESIDUE QUARTZ CRYSTAL STRUCTURE WELL ADVANCED IN RESIDUE PARTICLES FROM RUN NO. 14

sample chlorinate, but this figure represents only a maximum because some of the HCl in the trap could have been derived from other sources, such as hydrolysis of phosgene formed in cooler parts of the equipment. The chlorination mixture did not attack the quartz apparatus measurably.

Factors Affecting the Chlorination Rate. The curves of Fig. 3 show that for all runs there was an initial period, longer for some runs than for others, during which all chlorine entering the chlorinator was consumed in the formation of magnesium and iron chlorides at a minimum rate of 110 lb/hr/ft^3 of reactor volume. Heat generated was not measured in the experimental work, but the calculated heat generation, assuming the reaction represented by Eq. 7 to take place, was 106,000 Btu/hr/ft^3. It must be borne in mind that the above rates are correct only at the instant preceding chlorine detection in the exhaust gas, at which time chlorination was probably taking place throughout the entire bed. Earlier in the chlorination, the chlorine concentration probably approached zero before the entering gas had passed through more than a small fraction of the bed. As chlorination proceeded toward completion, the rate per unit volume of bed would drop until the chlorine supplied could no longer be consumed within the

TABLE I

Run No.	Particle Size (Tyler Mesh)	Temp. (°C)	Entering Gas (Mole Fraction)			Conversion (%)		Cl Accounted for (%)	Residue Analysis (%)		Silicon Halides Observed
			Cl_2	CO	Inert	Fe_2O_4	MgO		MgO	Fe_2O_3	
1	−150+200	700	0.50	0.50	.....	7.4	3.4	...	48.7	7.64	No
2	−150+200	810	.50	.50	.....	17.1	10.9	...	47.0	7.17	No
3	−150+200	1000	.50	.50	.....	Not Analyzed		...	....	....	No
4	−150+200	1000	.50	.50	.....	85.6*	47.1*	...	41.6*	1.56*	No
5	−48+65	1300	.50	.50	.....	54.0	29.4	...	43.1	4.6	No
6	−150+200	1300	.50	.50	.....	96.0	74.7	...	22.75	0.6	No
7	−250+270	1300	.50	.50	.....	91.8	59.8	...	31.70	1.0	No
8†	−150+200	1200	.50	.50	.....	99.0	72.5	...	24.3	0.17	Yes
9	−150+200	1100	.50	.50	.....	93.2	52.1	...	35.7	0.85	No
10	−150+200	1100	.34‡	.22	0.44 CO_2	....	10.0#	...	....	....	...
11	−150+200	1100	.25	.25	.50 CO_2	47.2	26.9	...	43.6	5.1	No
12	−150+200	1100	.25	.25	.50 N_2	60.0	30.6	100	43.05	4.02	No
13	−150+200	1200	.25	.25	.50 N_2	67.0	35.8	90	41.5	3.5	No
14	−150+200	1200	.35	.35	.30 N_2	90.5	83.2	98	16.7	1.5	Yes
15	−150+200	1200	.50	.50	.....	99.5	89.0	94	10.7	0.09	Yes
16	−150+200	1200	.45	.55	.....	86.0	70.0	90	25.5	1.91	No
17	−48+65	1200	.50	.50	.....	90.5	90.7	100	12.8	2.18	Yes
18	−150+200	1300	.50	.50	.....	93.3	76.3	92	21.7	1.01	Yes

*Run not completed because of plugging.
†Chlorine contaminated with air.
‡Mole fraction SiCl this run only.
#Estimate only. This run was not analyzed chemically.

available bed volume, at which point chlorine was detected in the exhaust gas. Further drop in reaction rate would result in increased exhaust gas chlorine concentration.

Shapes of the curves of Fig. 3 may be partially explained by consideration of the equation describing simultaneous diffusion of gaseous substances to and from a particle-gas interface:

$$N_A = \frac{D_A \pi A (P_{A_1} - P_{A_2})}{RTzP_{BM}} . \qquad (8)$$

The equation as written is valid only for the special case where transfer in both directions is equimolal. Transfer according to the reaction of Eq. 7 is equimolal under conditions such that no liquid chloride is present, which is the only situation discussed.

In olivine chlorination, where equimolal quantities of chlorine and carbon monoxide must diffuse through any inert gas layer around the particle as well as through inert gas in the interstices between crystals of any residue present, the diffusion rate of chlorine will be less than that of carbon monoxide because of the higher molecular weight of chlorine. The magnitude of the equilibrium constant for the chlorination reaction and the observed high initial rate for the reaction indicate that, as soon as enough residue is present on the particle surface to make the diffusion path length appreciable, the chlorine concentration P_{A_2} at the residue-particle interface will be essentially zero. The rate of chlorine diffusion to the particle-residue interface, therefore, controls and is equal to the rate of chlorination of the mineral. Carbon monoxide, magnesium chloride, carbon dioxide, and any other nonreacting gases present, may be considered as inert gases or component B in the above equation because their presence decreases chlorine diffusion.

At the beginning of a chlorination, where the value of z would be very small, representing only the thickness of the stagnant gas film around a particle, it might be expected that the rate of chlorine transport to the particle surface would then be very large. Microscopic examination of the residues showed that the effective diffusion path length between residue crystals was large compared with the path length through the stagnant gas films around a particle, once an appreciable amount of conversion had taken place. Chlorine transport to the residue-particle interface, and therefore the reaction rate, would be expected to decrease rapidly with increasing residue thickness.

The area of fresh particle surface available for chlorination per unit of chlorinator volume decreases as chlorination proceeds, approaching zero as chlorination nears completion. The chlorination rate can therefore be expected to approach zero as conversion approaches 100 per cent.

Removal of magnesium chloride from the particle-residue interface is accomplished by diffusion resulting from the magnesium chloride partial pressure gradient existing between the interface and the body of gas in the chlorinator. Any pressure gradient required to remove produced magnesium chloride that would result in a magnesium chloride partial pressure at the interface higher than that of saturation would cause the presence of liquid magnesium chloride. The actual chlorination rate would

(Continued on page 35)

Experimental Investigation of Laminar Heat Transfer from a Uniformly Heated Flat Plate at Mach 2.5*

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The problem of heat transfer by forced convection at supersonic speeds to or from flat plates at zero incidence has been essentially solved theoretically, if the flow is laminar; references 1, 2, 3, and 4 summarize the field. For the case of cones there is a considerable amount of experimental data, but for flat plates the experimental work is quite meager. Slack[5] has measured the heat-transfer cofficients for a cooled flat plate at a Mach number of 2.4 and for a Reynolds number range from 150,000 to 3,000,000. The laminar data of Slack gave a good check of the theory of Chapman and Rubesin,[6] except for points near the leading edge.

The present investigation was carried out in order to extend the experimental data for laminar heat transfer on flat plates to a lower range of Reynolds number. The data found did agree with the Chapman-Rubesin theory down to a Reynolds number of 20,000. Since the wind tunnel available was small, the size of the flat-plate model was very limited. Also, the stagnation temperature of the airstream being room temperature, it was decided to heat the model and determine the heat transfer from the plate to the airstream.

Test Equipment

Wind Tunnel. This investigation was carried to completion in the University of Washington Aeronautical Laboratory Supersonic Wind Tunnel No. 2. The wind tunnel, which has a two-dimensional test section with a test area of 1 by 2 inches and a nominal Mach number of 2.5, is capable of nearly unlimited continuous operation, drawing air from the room and exhausting it outside the building. (See Figs. 1, 2, and 3.) The stagnation conditions in the room are almost identical to the NACA standard day.

Wind-Tunnel Model. The flat-plate model (Fig. 4) was nearly a full-span plate. Because of the nature of the wind tunnel, the plate glass sides suck in during a run, and consequently the span of the tunnel is reduced slightly below the nominal value of one inch. The gap between the flat plate and the glass wall, estimated at about .002 inch, is believed to lie entirely inside the boundary layer of the wall.

R. E. Street

In order to maintain a constant temperature on the plate surface, a number of small heaters were used, instead of one heater which would give a rather arbitrary temperature distribution along the chord of the plate. The complexity of the data reduction was decreased by installing heaters on both sides of the flat plate in order to obtain a zero temperature gradient across the thickness of the model. Five heaters were imbedded in the top surface and four in the bottom surface. Also, each heater had to have an individual power supply and control and, in addition, its own thermocouple to indicate the temperature of the area which it heated.

Consequently, to facilitate all the heater and thermocouple leads and still keep a flat surface on top and bottom, a plate cross section in the form of an "I" was chosen, using the area of each side for wires. Since a great number of wires, some uninsulated, were required, it was decided to build up a plate of thin laminated plexiglas sheet. Plexiglas was chosen in preference to other plastics because of its thermal properties and relative ease in bonding.

The top surface of the flat plate was located approximately along the horizontal center line of the test area. To eliminate chordwise bending, a thin support strut was attached to the underside of the model and to the tunnel floor. By attaching the strut to the floor in only one place, it could rotate and pitch the model. Changing the angle of attack of the model was accomplished by raising or lowering a second strut which was attached to the model sting and the variable depth second throat.

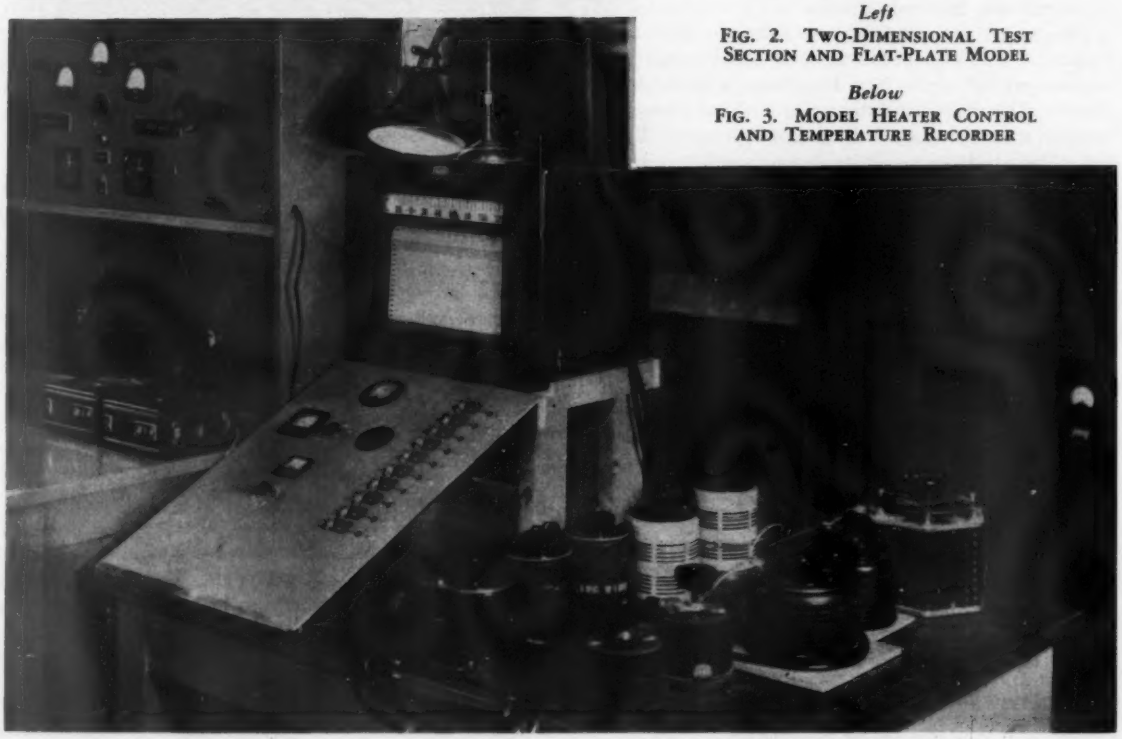
Heaters. Each of the heaters had its own power source and control (Fig. 3). This was accomplished

* Condensed and arranged from the thesis of D. A. Graf submitted for the degree of M.S. in Aeronautical Engineering, University of Washington, 1955.

Above
FIG. 1. 1"-BY-2" UWAL SUPERSONIC WIND TUNNEL NO. 2

Left
FIG. 2. TWO-DIMENSIONAL TEST SECTION AND FLAT-PLATE MODEL

Below
FIG. 3. MODEL HEATER CONTROL AND TEMPERATURE RECORDER



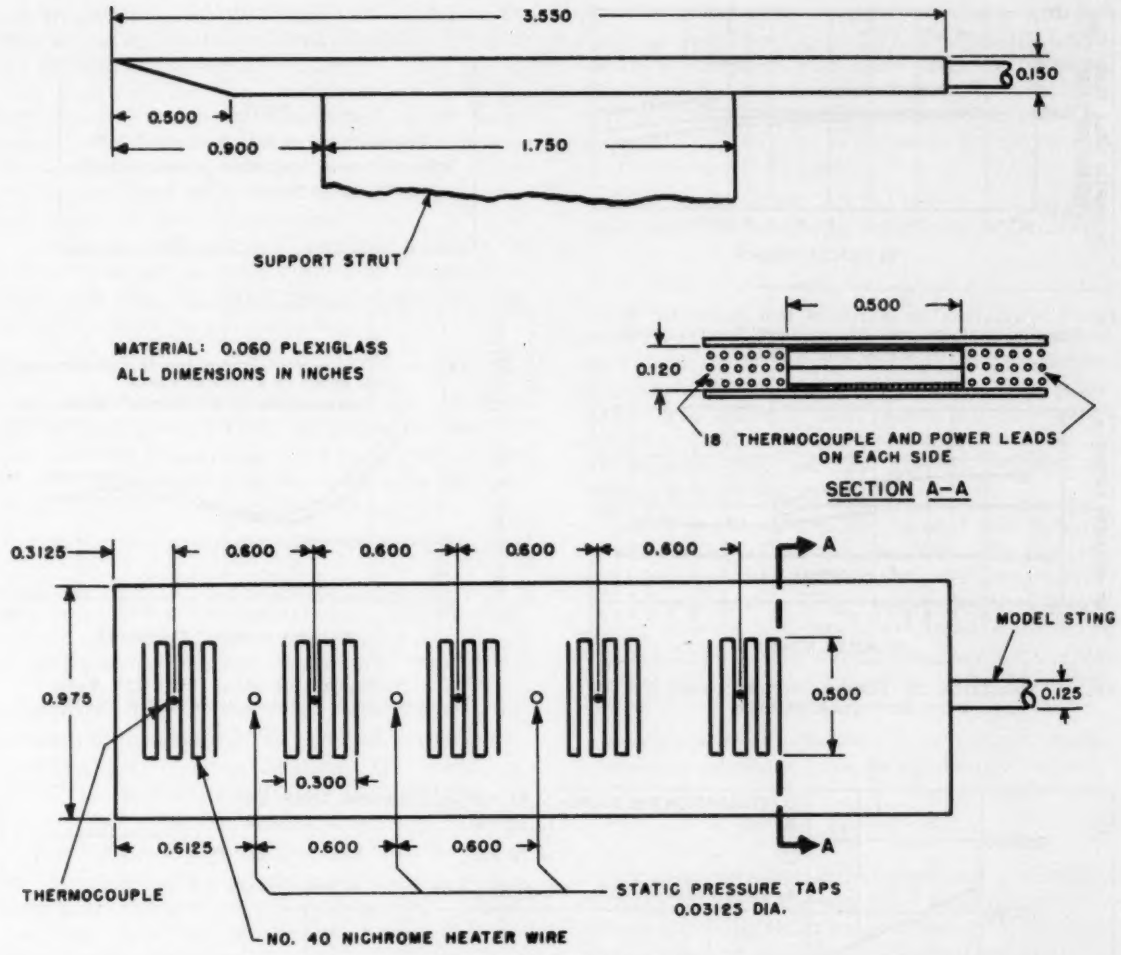


FIG. 4. FLAT-PLATE MODEL

by the use of nine powerstats or autotransformers, each with an output of 0-110 volts a.c. To reduce the number of electrical instruments needed, all nine heater circuits used a common side return. An ammeter was used in the circuit to give an indication of the local temperature of the nichrome heater wires. To keep the current less than 0.25 amp, the resistance of each heater was made to be 20 ohms or slightly larger.

Temperature and Pressure Measurements. The temperature in the vicinity of each heater was measured by a copper-constantan thermocouple, gage number 30. This temperature was in turn recorded by a 12-point Brown recorder which incorporates a self-balancing potentiometer (Fig. 3).

Static pressures along the wind-tunnel floor and on the flat plate were indicated by a 25-tube mercury manometer and were recorded photographically.

Test Procedure

The investigation was carried out in a Reynolds number range of 19,500 to 190,000. A slight change in the Reynolds number was accomplished by variation of the stagnation pressure. Also, data were taken at basically two different stagnation temperatures.

At the beginning of each run the model was unheated and assumed to be in an adiabatic temperature state after equilibrium was reached. The time to reach temperature equilibrium was approximately 20 minutes. Electrical power was then supplied and increased in an attempt to stabilize all nine temperatures at a nominal value of 100° F. The time for the entire model, top and bottom surfaces, to reach a uniform temperature was more than two hours. At the completion of the run, the power was stopped and the adiabatic wall temperature was again determined, for a check. From this type of a run the adiabatic

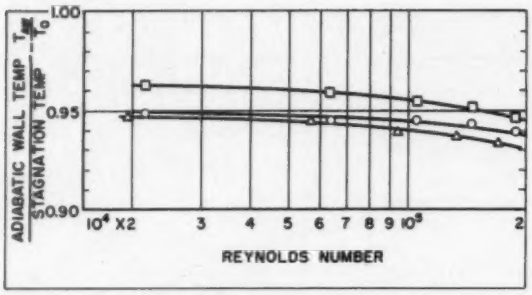


FIG. 5. VARIATION OF RATIO OF THE ADIABATIC WALL TEMPERATURE TO THE STAGNATION TEMPERATURE WITH REYNOLDS NUMBER

NOTE

Symbols used in Figs. 5, 6, and 7 indicate the same stagnation pressures and temperatures as shown in Fig. 8.

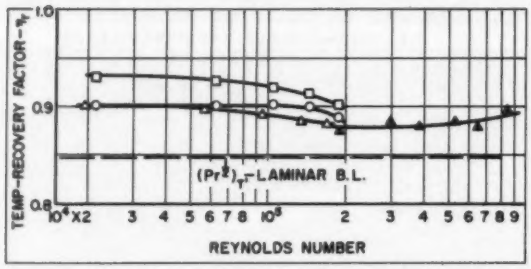


FIG. 6. VARIATION OF TEMPERATURE-RECOVERY FACTOR WITH REYNOLDS NUMBER

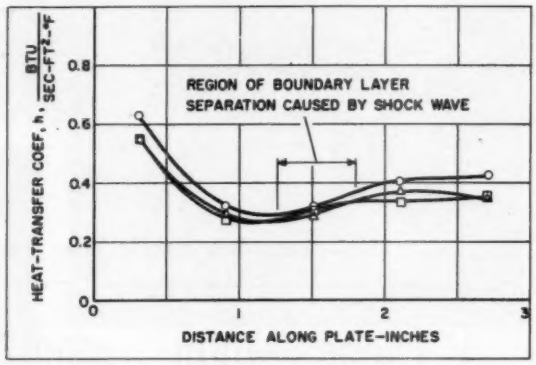


FIG. 7. VARIATION OF HEAT TRANSFER WITH DISTANCE FROM LEADING EDGE OF THE PLATE

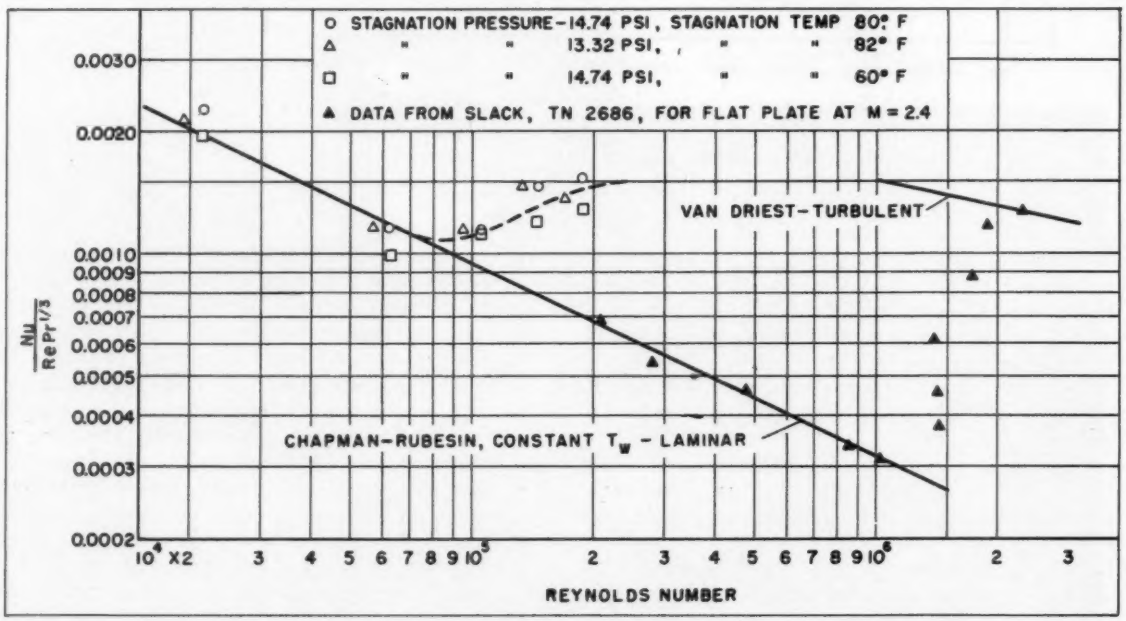


FIG. 8. COMPARISON OF EXPERIMENTALLY DETERMINED NUSSELT NUMBER WITH THEORY

wall temperature could be determined in addition to the heat transfer by the combined effect of forced and free convection and radiation.

To determine the free convection and radiation heat transfer, the model was heated to the same nominal 100° F and the power required to maintain this condition with no air flow was recorded. The difference of these values was thus assumed to be the heat transfer by forced convection.

For the run with reduced stagnation pressure, it was assumed that a small change in the pressure would not have any effect upon the no-flow heat transfer.

Experimental Results

Reynolds Number. The values of the Reynolds number were calculated from air properties obtained from reference 7. In determining these properties, a reference temperature, T',[4] was used. The value of T' was calculated from the following expression:

$$T' = T_\infty(1+0.032M_\infty^2)+0.58\,(T_w-T_\infty)\,, \qquad (1)^*$$

where the value of T_∞ was obtained from the supersonic flow tables and the value of M_∞. This temperature, T', seems to be more representative than either the free-stream or the wall temperature.

Adiabatic Wall Temperature. Figure 5 shows the variation of the adiabatic wall temperature with the chordwise distance along the plate. This curve is a plot of the ratio of the adiabatic wall temperature, T_{aw}, to the stagnation temperature, T_0, vs. the Reynolds number, $Re = xU_\infty/\nu$. The data found by the present investigation show a variation in the temperature ratio of only about 1 per cent. Based upon this curve, in all calculations involving the adiabatic wall temperature, a chordwise average will be used.

It should be mentioned that from previous data the thermocouple in the center of the plate will read the maximum spanwise temperature and the temperature will drop off on either side. These data indicated that about 0.9 of the measured temperature will be a representative value for the spanwise variation.

Recovery Factor. Values of the recovery factor, η_r, have been calculated, using the equation,

$$\eta_r = 1-\frac{T_0-T_{aw}}{T_0}\left[\frac{2}{(\gamma-1)M_\infty^2}+1\right]. \qquad (2)$$

These values can be seen in Fig. 6. This curve indicates that the recovery factor is about 5 to 10 per cent high in comparison with the theoretical value of $Pr^{1/2}$.

*The subscript ∞ refers to free-stream conditions, while T_w is the surface temperature of the plate.

However, these values compare very closely with the data from reference 4, page 1071. Perhaps the larger values, as compared with these other experiments, result from the excessive turbulence in the airstream or from an undue amount of moisture in the air. The drying bed used in these experiments did not remove all the moisture in the room air.

Heat-Transfer Rate. All the rate of heat-transfer values were calculated using the following expression:

$$\frac{Q}{A} = K\,\frac{E^2}{R}\,\frac{1}{bl}\,, \qquad (3)$$

where E^2/R is the actual amount of electrical power input required for heat transfer by forced convection at a uniform flat-plate temperature, the area, bl, is the surface area heated by each heater, and K is a numerical constant to convert from watts to Btu/sec. It was assumed that the area affected extended to midway between heaters on both sides.

Variation of the rate of heat transfer with distance from the leading edge of the plate follows the expected trend for nearly half of the plate length; then a sudden increase occurs. This can be attributed to the separation of the boundary layer caused by the interaction of a shock wave and the boundary layer. (See Fig. 7.) However, the data ahead of this separation showed the expected trend.

Heat-Transfer Coefficient. Heat-transfer coefficients were calculated from the equation,

$$h = \frac{Q}{A}\,\frac{1}{(T_w-T_{aw})}\,. \qquad (4)$$

Figure 7 indicates that, within experimental accuracy, neither a change in the stagnation temperature nor a change in the stagnation pressure has any appreciable effect on the heat-transfer coefficients. Here again the boundary-layer separation is clearly indicated.

Heat-Transfer Parameter. Probably the most significant heat-transfer parameter is the following expression:

$$\frac{Nu}{Re\,Pr^{1/3}}\,, \qquad (5)$$

where both the Nusselt number, hx/k, and the Reynolds number are the local values at any particular point. The theoretical curves of Chapman-Rubesin and van Driest for laminar and turbulent boundary layer are shown in Fig. 8. The data from this investigation show very good agreement with the Chapman-Rubesin curve. Again the separation to turbulent flow is sharply marked and indicates a trend toward the van Driest turbulent boundary-layer curve. For comparison of experimental data, some values from reference 5 have been included on this graph.

Conclusion

From the data this investigation has produced, the following summary may be made:

1. The Chapman-Rubesin theoretical curve for heat transfer through laminar boundary layers holds true in the lower Reynolds number range of from 19,000 to 195,000.

2. Heat-transfer data may be taken for either a heated or a cooled plate without any sacrifice in accuracy.

3. Boundary-layer separation has a very noticeable effect on the rate of heat transfer.

4. Moisture and turbulence in the air have a decided effect on the temperature-recovery factor.

5. It is possible to heat a model to a uniform surface temperature and thus forego any analytical corrections of the heat-transfer data.

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Engineering Research Dividends

Recent theses submitted for advanced degrees from the College of Engineering, University of Washington, will regularly appear in abstract form in *The Trend*. Complete copies of these theses are available for reference at the University of Washington Library. Address inquiries to the Director of the Engineering Experiment Station, University of Washington, Seattle 5.

OTTERBEIN, GLENN L., "Self-Diffusion of Methanol in the System Methanol-Water." M.S. in Chemical Engineering, 1955.

Self-diffusion coefficients of methanol in the system methanol-water were measured at 26.9° C by means of a scintillation-counting technique which involved the use of methanol tagged with carbon-14. The liquid mixture under study was placed and immobilized in two porous, stainless-steel disks. The liquid containing the radioactive methanol was placed in the top disk and a solution of the same composition containing ordinary methanol was placed in the bottom disk. The disks were held in the diffusion cell with the bottom disk resting against an anthracene scintillation crystal. As the radioactive molecules from the top disk diffused through the liquid in the bottom disk and contacted the crystal, their radiation was detected by a scintillation-counting assembly. In this way a continuous record of the concentration of radioactive molecules at the crystal face was obtained. From a curve of counts per minute versus time, the diffusion coefficient was calculated from Fick's second law.

The reliability of the method was confirmed by measuring the value for a self-diffusion coefficient of methanol in the system methanol-ethanol. The value obtained was within 2 per cent of the data reported by another investigator who used an entirely different method.

The mutual diffusion coefficients of methanol in the system methanol-water were compared with the measured self-diffusion coefficients and an attempt was made to correct for the deviations. The corrections applied were based on two current theories of liquid diffusion by Lamm and Prager.

GILES, H. L., JR., "Theoretical Ground Plane Effects on Span Loading for Wings Having No Sweep," M.S. in Aeronautical Engineering, 1955.

A method is shown for calculating the span load distribution of an unswept wing in the presence of a ground plane. The wing itself is replaced by a bound vortex which may be regarded as the line of aerodynamic centers of the wing sections and is straight and normal to the plane of symmetry of the wing. The field of the wing is represented by the bound vortex, its trailing vortex sheet, and the reflected image vortex systems of both. All vortices are parallel to the ground plane. Downwash velocities are governed by Prandtl's downwash relation, together with another relation introducing the effects

of the presence of the ground plane. The circulation is represented by a Fourier's Series, the constants of which are determined by selection of a finite number of points along the span and by the consequent solution to a system of linear algebraic equations. Span load distributions are calculated for wings of aspect ratio, 6, with taper ratios of 1/3, 2/3, and 1, at a distance of .05 span above the ground. In each case, the total lift increase at constant angle of attack agrees with previously published data, while the spanwise center of lift is moved inboard from its position in free air.

HAWKINS, S. E., "Slope Deformation and Safety as Related to Railway Landslide Problems." M.S. in Civil Engineering, 1955.

A summary of stress-strain relationships of earth materials and slope deformation prior to and after failure is presented, with examples of actual landslide problems. In addition to a review of railway landslide detector devices used at present, a proposed device is recommended to provide better protection against the failure of an entire slope by slumping. Also proposed is a means for determining the location of deformations within a slope by checking the alignment of a plastic pipe placed within the slope.

The results of a study of increasing slope safety by unloading the slope shows that benching is more economical than slope reduction. Benching, the removal of earth material from the crest of a slope, requires less volume of removal and less width of excavation for a particular increase in safety factor of the slope as compared to slope reduction. Curves showing this comparison and proper bench dimensions are presented for original slopes of 1 (horizontal) to 1 (vertical), and 2 to 1.

RISDAL, R. E., "The Effect of Compressibility on Downwash Behind a Sweptback Wing at Subsonic Speeds," M.S. in Aeronautical Engineering, 1955.

Downwash calculations have been made behind a wing with 45° of sweepback, an aspect ratio of 5.1, and a taper ratio of 0.385 at Mach numbers of 0, 0.6, 0.8, 0.89, 0.925, and 0.96. The results compared well with experimental data available up to the critical Mach number. As a rule the downwash decreases with increasing Mach number, although, at stations where the spanwise loading increased with increasing Mach number, the downwash near the center of the wake tended to increase at the higher Mach numbers. The downwash near the center of the wake is very critically dependent upon variation of the spanwise loading distribution.

Ninth Northwest Conference on Road Building

THE NORTHWEST CONFERENCE ON ROAD BUILDING will be held February 20-21, 1956, at More Hall, the University of Washington. Each year several hundred engineers and officials from the Pacific Northwest attend these meetings, which are intended to serve as a forum where local, state, and federal engineers can exchange views with each other and with the contractors and suppliers who also attend in considerable numbers. Meetings alternate years are held at the Oregon State College at Corvallis.

The 1956 meeting comes during a critical period for road development—when a turning point in national road policy will be the subject of Congressional debate. Because of the importance of this issue, the 1956 Conference will devote more time to highway policy and less to the technology of road building than in previous Conferences.

The following tentative program plans are announced:

FEBRUARY 20

1. **"What the Clay report could mean to the Pacific Northwest"**
2. **"Two bottlenecks and what's to be done about them"**
3. **Symposium: "New needs for roads"**

This series of talks is intended to bring out the principal factors which make it necessary—or profitable—to spend more money on road building; in other words, the situations that led to the Clay report. It is planned to run this off as a sort of modified panel discussion on six topics: *Roads for regional development; What price local roads? Flight to the suburbs; Urban congestion; Upgrading the interstate system.*

FEBRUARY 21: PANEL DISCUSSIONS

1. **"How the Washington State Highway Commission operates"**
2. **"How the Washington State Legislature handles roads and streets"**
3. **"How State highways are planned, designed, constructed, and operated"**
4. **"What should we spend for roads and streets, and how should we pay for them?"**
5. **"Sharing responsibility for road and street costs in Washington State"**

As in the past, it is planned to publish the *Proceedings* of the Conference. These *Proceedings* have attracted wide interest. Requests for copies have come from many states and from some foreign countries.

A Model Study of Sewage Pollution in Puget Sound

(Continued from page 9)

turbulent supercritical-flow velocity which occurs in this channel, and from which, on the outgoing tide, it is jetted northward up Colvos Passage, thence out across the Sound toward a point slightly south of Alki Point.* There some of the sewage turns north, while a smaller part turns south to return to the Narrows for further mixing and jetting through Colvos Passage as before. Our studies indicate that about two-thirds of any sewage discharged at Brace Point will go south and possibly one-third will go north. Sewage discharged to the Sound further south has a still smaller proportion moving northward. Similarly, sewage discharged north of Alki Point will have decreasing increments moving southward.

If one summates the areas under plotted tidal current curves for Puget Sound (north of Seattle), East Passage (Fig. 2), and Colvos Passage on a day of approximately average annual tides (Feb. 16, 1954) in this area, the following average net surface movement is indicated:

Puget Sound = 2.0 nautical miles per day, North
East Passage = 1.5 nautical miles per day, South
Colvos Passage = 13.9 nautical miles per day, North

These figures corroborate the relative tidal movements shown in Figs. 2 and 3, with the Narrows acting as a jet pump to draw in Puget Sound water from East Passage and pump it northward through Colvos Passage and thence across the Sound toward Alki Point, thus producing a clockwise circulation around Vashon Island.

The Narrows is one of the two areas in Puget Sound where turbulent, supercritical flow with its effective mixing occurs. The other effective mixing area is at the entrance to Admiralty Inlet from the Strait of Juan de Fuca. Here the high salinity water from the Strait enters the Sound over an entrance sill and plunges downward into the rapidly deepening channel of the Sound, thus moving southward, while the outflowing brackish water with its remaining pollutional load, shuttles back and forth with the tides as it flows out into the Strait (Fig. 4). Effective vertical mixing occurs here both because of this topographic feature and also because of supercritical velocities which occur during part of the tidal cycle. Note also that some of the outgoing water is dragged back up-Sound by the incoming bottom flow. However the major portion of the polluted water moves out into the Strait and eventually finds its way into the Pacific Ocean.

* The movements in the Tacoma Narrows and up Colvos Passage are not shown in Fig. 3.

In concluding this greatly abbreviated description of a portion of the studies made with the Oceanography Department's model of Puget Sound, we wish to express the conviction that much useful information can be obtained concerning water and sewage movements in tidal estuaries at much less cost than has been expended on many model studies. More highly accurate or quantitatively dpendable results may require larger scales than here used, but for general water movements and the effects of topographic features upon them, or for the relative desirability of any of several outfall sites (which was the present objective), properly designed and constructed small-scale models can greatly aid engineering judgment.

We wish also to express appreciation to the Oceanography Department, University of Washington, and especially to Mr. John H. Lincoln and Prof. Maurice Rattray of the Department's staff, for permission to use the model, for their continuous help and advice in carrying out our research study, and for their having developed ingenious instruments for controlling, measuring, and recording the essential operations required for the successful completion of this investigation.

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WHEN IS AN ENGINEER A PROFESSIONAL?

(Continued from page 1)

branch of the profession, just as we expect the doctor to keep up to date with the latest uses of anesthetics, the wonder drugs or the most modern surgical techniques, or as we expect the lawyer to keep up to date on new legislation, precedent setting cases and Supreme Court decisions.

Unlike the non-professional employee, no matter how highly skilled that non-professional may be, the engineer must himself make this effort as an individual to keep up to date with developments in his particular branch of the profession. . . .

Still another responsibility the engineer has to industry is adherence to his professional code of ethics. . . . If an engineer counts himself a full-fledged member of his profession, it seems to me that we in industry have a right to expect that he knows, is aware of, upholds, and operates in accordance with, the canons or code of ethics of his profession.

Finally, industry expects that if engineers are to claim engineering as a profession, they themselves have to make it one. To date engineers in great numbers seem to have been unwilling to face up to this responsibility.

Magnesium from Olivine *via* Chlorination: A Possibility

(Continued from page 26)

therefore be very sensitive to temperature within the temperature range where the necessary interface partial pressure would result in the presence of liquid magnesium chloride. Chlorine-carbon monoxide diffusion through liquid magnesium chloride is extremely slow.[12]

Results of the experimental runs are in accord with the foregoing considerations. Reduction of the chlorine partial pressure from 0.5 to 0.25 atmospheres, as was done in Runs No. 11, 12, and 13 by the addition of inert gas to an equimolal carbon monoxide-chlorine mixture, reduced the initial numerical value of the term, $(P_{A_1}-0)/P_{BM}$ in Eq. 8 by a factor of 2.5. Only a small residue thickness was required to reduce the chlorination rate below that capable of consuming all chlorine supplied to the experimental bed, and chlorine was noted in the exhaust gas soon after the start of the run. The concentration of chlorine in the exhaust gas increased rapidly as the residue layer increased in thickness.

A relatively small excess of carbon monoxide was employed in Run No. 16. No chlorine whatever was observed in the exhaust gas of this run until chlorination had progressed to a much greater extent than on previous runs. An excess of carbon monoxide would ensure that the concentration of chlorine in the equilibrium represented by Eq. 1 would always be very nearly zero at the particle-residue interface. Once chlorine did appear in the exhaust gas of this run, its concentration increased very rapidly until the run was discontinued. The sudden, rapid increase of exhaust gas chlorine concentration could have been due to the existence of the saturation partial pressure of magnesium chloride at the interface after development of a certain diffusion path length.

Fluidization Studies. Following completion of the work described, a batch of olivine mineral of appropriate particle-size distribution was fluidized in a 30-mm diameter tube at room temperature, using air as the fluidizing medium. Data obtained were corrected to the expected operating conditions, using indirectly an equation derived by Ergun[15] for the calculation of pressure drop in fixed porous beds. An estimate was made of the minimum superficial gas velocity required for fluidization at 1300° C, assuming a carbon monoxide-chlorine mixture as the fluidizing medium, instead of air. Inasmuch as this estimated gas velocity was less than that actually used in the fixed bed, a good possibility would seem to exist for the efficient chlorination of olivine in a fluidized bed. (No fluidization occurred in the fixed bed shown in Fig. 2 because gas flow was downward through the bed.)

Future Work

The information obtained in the present work with regard to olivine chlorination may be summarized as follows:

1. The hypothetical reaction represented by Eq. 7 has been demonstrated to go substantially to completion for particle sizes up to 48-mesh when the temperature is high enough to volatilize substantially all of the magnesium chloride formed.

2. The rate of the reaction was higher by a factor of 150 than that reported by Ramsey[16] and Mantell[17] for the chlorination of magnesium oxide at 900° C, and remained this high through conversion of varying percentages of mineral up to 65 per cent.

3. The rate of reaction in the presence of fresh mineral is very high, even with a dilute chlorine-carbon monoxide mixture. One pass through a countercurrent-flow type of apparatus should suffice for the reaction of all chlorine supplied.

4. The problem of silica chlorination at high temperatures is not nearly so serious as earlier investigators have supposed.

5. Complete separation of product chloride and silica residue can be easily obtained.

6. It appears possible that a fluidized-solids type of chlorinator might be constructed and operated satisfactorily.

Raw material costs per pound of magnesium metal, using the reaction of Eq. 7 and recycling chlorine recovered in the electrolytic cell, would be small. With rock at $10.00 per ton, coke at $20.00, electric power at 3 mills per kilowatthour, and assuming the total power requirement to be 10 kwhr per pound of metal, raw material costs per pound of magnesium metal would be about $.05. If a fluidized-solids chlorinator could be operated satisfactorily, anhydrous magnesium chloride suitable for electrolytic cell feed could very probably be obtained at less cost than by the present commercial process, and certainly with greatly reduced capital investment.

It is not to be inferred that magnesium metal production from olivine is about to become a reality, but the information obtained in the present work, only incompletely described in this paper because of space limitation, and the foregoing estimate of raw material costs do provide great incentive toward further work. A laboratory-scale fluidized-solids chlorinator has been constructed and will be placed in operation in the near future. Considerable work has been done on the problems of metal chloride condensation, heat recovery, and chloride purification. Perhaps, within

the foreseeable future, the work of many investigators over the years will bear fruit, and magnesium metal from olivine will become a commercial reality.

NOMENCLATURE

N_A = moles component A transferred per unit time per unit area
D_A = diffusivity of component A
π = total pressure
P_{A_1} = partial pressure of component A in the body of the gas phase
P_{A_2} = partial pressure of component A at the fresh particle surface-gas phase interface, or at the particle-residue interface
R = gas content
T = absolute temperature
z = effective diffusion path length
P_{BM} = log mean partial pressure of component B

ACKNOWLEDGMENT

The author wishes to thank Dr. L. N. Johanson, of the Department of Chemical Engineering, for his assistance as supervisor of the olivine chlorination project on which the author's M.S. thesis and this article are based.

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A new addition to the McGraw-Hill Series in Civil Engineering is the text, *Fundamentals of Transportation Engineering*, by Robert G. Hennes, Professor, and Martin I. Eske, Associate Professor, of Civil Engineering.

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Project 183. Transmission Lines. A. V. Eastman, Professor of Electrical Engineering, Supervisor; Sita Bai Dasu, Research Assistant.

Project 184. Kinetics of Olivine Chlorination. L. N. Johanson, Assistant Professor of Chemical Engineering, Supervisor; K. B. Bengtson, Research Assistant.

Project 185. Plastic Design. D. D. Vasarhelyi, Assistant Professor of Civil Engineering, Supervisor; H. Erlijman, Research Assistant.

Project 186. Supersonic Flow Channel for Study of Base Pressure and Problems. P. J. Waibler and M. E. Childs, Assistant Professors of Mechanical Engineering, Supervisors; U. Lapins, Research Assistant.

Project 187. Electronic Analog Computer for Airplane Dynamics. R. E. Street, Professor of Aeronautical Engineering, Supervisor; Morito Ii, Research Assistant.

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Project 193. Simulation of Nonlinear and Time-Delay Systems by Analog Methods. J. H. Fisher, Assistant Professor of Electrical Engineering, Supervisor; J. J. McBride, Research Assistant.

Project 194. Dielectric Loading of Waveguides. G. Held, Assistant Professor of Electrical Engineering, Supervisor; W. V. Kiskaddon, Research Assistant.

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